Electron Energy Distributions in the Extended Gas Nebulae associated with High-z AGN: Maxwell-Boltzmann vs. $\kappa$-distributions

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ABSTRACT

Emission line observations together with photoionization models provide important information about the ionization mechanisms, densities, temperatures, and metallicities in AGN-ionized gas. Photoionization models usually assume Maxwell-Boltzmann (M-B) electron energy distributions (EED), but it has been suggested that using $\kappa$ distributions may be more appropriate and could potentially solve the discrepancies in temperatures and abundances found in HII regions and Planetary Nebulae (PNe). We consider the impact of the presence of $\kappa$ distributions in photoionized nebulae associated with AGN and study how this might affect spectral modelling and abundance analyses for such regions. Using the photoionization code MAPPINGS I we compute models adopting M-B and $\kappa$ distributions of electron energies, and compare the behaviour of emission line ratios for different values of $\kappa$, gas metallicity, density, ionization parameter and SED slope. We find that the choice of EED can have a large impact on some UV and optical emission lines emitted by photoionized nebulae associated with AGN, and that the impact of adopting a $\kappa$ distribution is strongly dependent on gas metallicity and ionization parameter. We compile a sample of line ratios for 143 type 2 AGN and compare our models against the observed line ratios. We find that for 98 objects $\kappa$ distributions provide a better fit to the observed line ratios than M-B distributions. In addition, we find that adopting $\kappa$-distributed electron energies results in significant changes in the inferred gas metallicity and ionization parameter in a significant fraction of objects.

Key words: galaxies: active, quasars: emission lines

1 INTRODUCTION

Active Galactic Nuclei (AGN) are compact objects found at the centre of galaxies. They are believed to be powered by the accretion of material onto supermassive black holes in the hearts of galaxies (e.g. Jones & Lambourne 2004), and are an important source of feedback potentially influencing the evolution of their host galaxies (e.g. Springel et al. 2005; Morganti et al. 2005; Croton et al. 2006; Moe et al. 2009; Cano-Díaz et al. 2012). Their spectra show strong emission lines from various chemical elements in a wide range of ionization states (e.g. Kriss et al. 1992; Netzer 1997; Véron-Cetty & Véron 2000; Collins et al. 2005). A detailed analysis of the emission line spectra provides information on the physical conditions of the emitting gas, including its density, temperature, chemical composition and ionization state (e.g. Villar-Martín et al. 1999b, 2001; Humphrey et al. 2008). Properties are usually estimated using photoionization models (e.g. Binette et al. 1996; Collins et al. 2009; Silva et al. 2018; Feltre et al. 2016). Photoionization codes compute recombination rates, ionization rates, and fluxes of spectral lines, which depend on the shape of the electron velocity (or energy) distribution, usually assumed to be a Maxwell-Boltzmann (M-B) distribution (e.g. Villar-Martín et al. 1997; Moy & Rocca-Volmerange 2002; Humphrey et al. 2008; Matsuoka et al. 2009; Silva et al. 2018).

The assumption that the velocity distribution of the free electrons in gaseous nebulae are described by a M-B distribution dates back to, at least, the 1930s, when the treatments of the physical state of Planetary Nebulae (PNe) already used this distribution (e.g. Bohm & Aller 1947; Hebb & Menzel 1940). This assumption is based on the electron thermalization timescale, the timescale a free electron requires to become thermalized and described by the M-B distribution (e.g. Bohm & Aller 1947; Spitzer 1962). It is usually assumed that free electrons share their energy with the neighbouring medium so rapidly that they become thermalized before they excite any emission line. The thermalization timescale of energetic electrons is proportional to the cube of their velocity (Spitzer 1962), hence plasmas with high energy electrons will take longer to reach equilibrium than plasmas with cooler electrons. Since the thermalization timescale depends on the frequency of collisions, electron energies in high density gas will equilibrate faster than in low density gas.

The suggestion that the electron velocity distribution may be non-M-B also dates back to the 1930s, when Hagihara (1939a,b) proposed that the velocity distributions in PNe depart significantly from a M-B distribution. Later, empirical kappa ($\kappa$) distributions were...
used to describe magnetospheric electron observations (e.g. Binsack 1966; Olbert 1968; Vasyliunas 1968). Since then, $\kappa$ electron energy distributions have been directly measured in several solar system plasmas. They are present in the solar wind (e.g. Gloeckler et al. 1992; Maksimovic et al. 1997), in the outer heliosphere and the inner heliosheath (e.g. Decker & Krimigis 2003; Heerikhuisen et al. 2008), in planetary magnetospheres, including magnetosheath (e.g. Binsack 1966; Gloeckler & Hamilton 1987; Krimigis et al. 1983, 1986; Olbert 1968), and magnetospheres of planetary moons (e.g. Jurac et al. 2002; Moncuquet et al. 2002).

It is clear that $\kappa$ distributions are prevalent in solar system plasmas, but not until recent years has the possibility of $\kappa$ distributions in extrasolar gaseous nebulae been significantly explored. Nicholls et al. (2012) used the $\kappa$ distribution in order to resolve longstanding discrepancies in the measurements of abundances and temperatures in HII regions and PNe, principally the discrepancies between electron temperatures derived from collisionally excited lines (CELs) and recombination lines (RLs), and discrepancies between chemical abundances inferred from RLs and CELs (e.g. Wyse 1942).

Following the work of Nicholls et al. (2012), a number of subsequent studies have addressed the possibility that $\kappa$ electron energy distributions are present in gaseous nebulae, in place of a M-B distribution (e.g. Binette et al. 2012; Dopita et al. 2013, 2014; Nicholls et al. 2013; Storey & Sochi 2013, 2014; Mendoza & Bautista 2014; Humphrey & Binette 2014; Ferland et al. 2016; Zhang et al. 2016) with varied conclusions. While Nicholls et al. (2012, 2013); Binette et al. (2012); Humphrey & Binette (2014) found that using $\kappa$ distributions solved some of the problems encountered when attempting to reproduce the temperatures observed in HII regions, PNe and AGN, Storey & Sochi (2013); Mendoza & Bautista (2014); Zhang et al. (2016); Ferland et al. (2016); Draine & Kreisch (2018) found little or no evidence for the existence of $\kappa$ distributions in these objects.

Although $\kappa$ distributions were initially criticised for lacking a theoretical justification, Tsallis et al. (1995) showed how these distributions can appear using entropy considerations and it has also been shown that they can arise from Tsallis’s non-extensive statistical mechanics (e.g. Leubner 2002; Livadiotis & McComas 2009). For a review on $\kappa$ distributions and on the mechanisms proposed to generate them in space plasmas see Pierrard & Lazar (2010). Supra-thermal electrons are present in the gas due to the photoionization process, but the question is how important are these electrons in comparison to the thermal ones. If the timescale at which energetic electrons enter the gas is of the same order or smaller than the thermalization timescale, then a high energy tail in the electron energy distribution could persist and these electrons may be able to affect the emitted spectrum, otherwise, the signature of a $\kappa$ distribution would disappear. Nicholls et al. (2012) proposed several mechanisms capable of inducing $\kappa$ distributions, including accelerations induced by shocks, photoionization by a hard radiation source, photoionization of dust (Dopita & Sutherland 2000), suprathermal atom or ion heating, X-ray ionization, and magnetic reconnection (e.g. Bradshaw & Raymond 2013).

Here, we consider the presence of $\kappa$ distributions in extrasolar AGN photoionized nebulae and we study how this might impact on spectral and abundance analyses for such regions. The degree of ionization in the gas has a dependence on the form of the electron energy (or velocity) distribution, and thus if $\kappa$-distributed electrons are present they may affect the observed spectra and this will affect the derivation of the physical conditions present in the nebulae. For example, if the free electrons follow a $\kappa$ distribution and the temperature is derived assuming that they follow a M-B distribution then the inferred temperature will be incorrect (e.g. Owocki & Scudder 1983).

In this work, we compare the emission line fluxes predicted by photoionization models using M-B distributions with predictions obtained using models that assume $\kappa$ distributions of electron energies, in an attempt to understand how they differ and what changes can be expected when using different distributions. We will be comparing the behaviour of emission line ratios using different electron energy distributions for several values of metallicity, density and ionization parameter. Choosing the appropriate photoionization model is crucial since we are relying on these models to study the properties of photoionized nebulae associated with AGNs.

This paper is organized as follows. In Section 2 we describe the $\kappa$ distribution in more detail. In Section 3 the photoionization models used in this work are presented. The results are shown in Section 4. In Section 5 we compare our model calculations with observed line ratios and in Section 6 the results are discussed. Finally, we summarise our main results and final conclusions in Section 7.

2 THE $\kappa$ DISTRIBUTION

$\kappa$ distributions describe stationary state systems outside of thermal equilibrium. In this system there are more particles with high energies than in a system in thermal equilibrium (i.e. a system described by the M-B distribution). Following Vasyliunas (1968) and Nicholls et al. (2012) the fraction $f(E)$ of electrons having energies between $E$ and $E + dE$ for the $\kappa$ distribution is given by

$$f_\kappa(E)dE = \frac{2n_e}{\sqrt{\pi}} \frac{\Gamma(\kappa + 1)}{(\kappa - 3/2)^{\frac{\kappa}{2}} \Gamma(\kappa - 1/2)} \sqrt{\frac{E}{(k_B T_e)^{3/2}}} (1 + E/[E - \Gamma(k - 3/2)k_B T_e])^{-\kappa} dE,$$

where $n_e$ is the electron density, $\Gamma$ is the gamma function, $\kappa$ is a parameter that characterizes the distribution and varies from $3/2 < \kappa < \infty$, $k_B$ is the Boltzmann constant, and $T_e$ is the non-equilibrium temperature that characterizes the mean kinetic energy ($T_e = \langle E \rangle / (1.5k_B)$).

The $\kappa$ parameter measures the departure from an equilibrium distribution. As $\kappa$ increases the fraction of high energy electrons decreases. At the limit $\kappa \rightarrow \infty$, the energy $\kappa$ distribution reduces to the M-B distribution,

$$f_{\text{M-B}}(E)dE = 2n_e \sqrt{\frac{E}{k_B T_e}} \left( \frac{1}{k_B T_e} \right)^{3/2} \exp\left(-\frac{E}{k_B T_e}\right) dE,$$

where $T$ is the kinetic temperature (electron equilibrium temperature) and the other quantities are the same as in the previous equation. It has been shown that the physical meaning of the temperature for $\kappa$ distributions is the same as the kinetic temperature for a Maxwellian (e.g. Meyer-Vernet et al. 1995; Livadiotis & McComas 2009).

Fig. 1 compares $\kappa$ electron energy distributions for several values of $\kappa$ (different level of deviations from equilibrium) with a M-B distribution, all at the same temperature. In comparison with a M-B distribution, $\kappa$ distributions reach their maximum at lower energies, and as $\kappa$ decreases the peak of the function moves to lower energies. In a $\kappa$ distribution there are more electrons both with high and low kinetic energies when compared with an M-B. At intermediate energies there is a depletion of electrons.
3 MAPPINGS 1E MODELS

We used the photoionization code MAPPINGS 1e (Binette et al. 1985; Ferruit et al. 1997; Binette et al. 2012), which includes the option of considering \( \kappa \) distributions of electron energies instead of the equilibrium M-B distribution (see Binette et al. 2012).

To calculate the excitation and de-excitation rates of the collisionally excited lines for a \( \kappa \) distribution, Binette et al. (2012) used the correction factor derived by Nicholls et al. (2012), Binette et al. (2012) derived an expression for the temperature to compute recombination rates, and implemented the enhancement of collisional ionization using two sets of correction factors that depend on the ionization process. For more details on how the \( \kappa \) distribution was implemented on MAPPINGS, 1e see Binette et al. (2012).

The photoionization models consider an isochoric, plane-parallel slab of gas which is illuminated by a power-law spectrum of ionizing radiation \( (S_\nu \propto \nu^\kappa) \). The intensity of the radiation is given by the ionization parameter\(^1\), \( U \), which indicates the intensity of the ionizing radiation as felt by the cloud. We adopted ionization-bounded termination and ended the calculation when the ionization fraction of hydrogen drops below 0.01. Our models did not consider depletion of metals unto dust.

Our goal is to investigate how line ratio predictions change depending on the adopted electron distribution function. In order to do this we compute a large grid of photoionization models using M-B and \( \kappa \) electron energy distributions for identical parameters. In addition to models using the M-B distribution, we compute models where \( \kappa \) has the values 5, 10, 20, and 40. Nicholls et al. (2012) suggested that for PN and HII regions a value of \( \kappa \) in the range \( 10 \leq \kappa \leq 20 \) would be enough to solve the discrepancies. However, we choose a wider range to explore all possibilities.

We compute sequences of models in which \( U \) varies over the range \( 10^{-5} - 1.8 \). We investigate values of the power-law index \( \alpha = -2, -1.5, -1 \) which are consistent with values adopted in the literature (e.g. Robinson et al. 1987; Villar-Martín et al. 1997; Zheng et al. 1997; Radovich et al. 1998; Groves et al. 2004). The models computed assuming \( \alpha = -1.5 \) and \( \alpha = -2 \) have a high energy cut-off for the ionizing continuum of \( 5 \times 10^2 \) eV, to ensure that the mean ionizing photon energy matches the value derived for radio-loud AGN (e.g. Mathews & Ferland 1987). Models with an ionizing continuum with \( \alpha = -1 \) assume a cut-off energy of 1000 eV to ensure that the mean photon energy matches that of the \( \alpha = -1.5 \) power-law.

For the hydrogen density we assume \( n_H = 100, 10^4, 10^6 \) cm\(^{-3} \) following the results from McCarthy et al. (1990); Villar-Martín et al. (1999b).

For the metallicity (defined as \( Z/Z_\odot \)) we consider \( Z/Z_\odot = 0.1, 0.5, 1.0, 2.0, 3.0 \). The gas metallicity is expressed with respect to the solar abundance set of Asplund et al. (2009). The chemical abundances have been scaled with all metals scaled proportionally to oxygen except nitrogen and carbon. Nitrogen and carbon are scaled quadratically with oxygen (e.g. Henry et al. 2000) when \( Z_{\odot}/0.3Z_{\odot} \). Below this metallicity they are scaled linearly (N/H \( \propto \) O/H, e.g. Henry et al. 2000; Vernet et al. 2001).

A summary of all the parameters used in the photoionization models is presented in Table 1. In total, the grid has \( 100 \) \( U \) x \( 5 \) \( Z \) x \( 3 \) \( n_H \) x \( 5 \) \( \kappa \) = 7500 models.

4 RESULTS

In this section we present the results of the photoionization model calculations. We compare the results obtained using M-B and \( \kappa \) electron energy distributions when different parameters are adopted. We hereafter refer to \( \kappa / \) M-B of a given emission line as the quotient between the line flux obtained when a \( \kappa \) distribution is used with respect to the same line flux assuming a M-B distribution. In Figs. 2 to 10 we show results from our grid of photoionization models, for emission lines in the IR, optical, and UV.

The figures are organized as follows; each emission line is shown for different model parameters, \( \kappa \) and M-B electron energy distributions. Each panel in the figures corresponds to different assumptions concerning the gas metallicity, \( Z \).

4.1 Infrared emission lines

We show our predictions for the following lines \([\text{ArIII}]\lambda 9 \mu\text{m}, [\text{NeV}]\lambda 14 \mu\text{m}, [\text{SIV}]\lambda 10.5 \mu\text{m}, [\text{NeII}]\lambda 12.8 \mu\text{m}, [\text{NeIII}]\lambda 15.6 \mu\text{m}, [\text{NeV}]\lambda 24 \mu\text{m}, [\text{OIV}]\lambda 25.9 \mu\text{m}, [\text{OII}]\lambda 37 \mu\text{m}, [\text{NII}]\lambda 122 \mu\text{m}, [\text{OI}]\lambda 63 \mu\text{m}, [\text{OIII}]\lambda 88 \mu\text{m}, and [\text{CI}]\lambda 158 \mu\text{m} \) .

In general, our calculations show that the flux of infrared (IR) emission lines is not enhanced when assuming \( \kappa \) distributions of electron energies in the photoionization models. On the contrary, the line fluxes are usually predicted to be weaker for \( \kappa \) distributions.

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\(^1\) \( U = \frac{Q}{4\pi r^2 n_H} \), where \( Q \) is the ionizing photon luminosity, \( r \) is the distance between the ionized cloud and the ionizing source, \( c \) is the speed of light and \( n_H \) is the hydrogen gas density.
Our results are similar to those in Nicholls et al. (2012, 2013); Doptia et al. (2013) who showed that the effect of $\kappa$ on the IR lines was very weak. To illustrate this, we show the ratio between predictions assuming $\kappa$ and M-B distributions for all the lines as a function of the excitation energy of each line. The results cover different values of $\kappa$ and $Z$.

Similar results are obtained across all emission lines: $\kappa$ distributions shift the line ratios towards lower fluxes. The shift becomes larger for low values of $\kappa$, i.e., for larger deviations from equilibrium. As the metallicity increases the predictions assuming $\kappa$ distributions approach the predictions from M-B distributions.

Similar results are obtained for $U$=0.01, as shown in Fig. 3. The lines are more intense when a Maxwellian is used. With such ionization parameter the differences between model predictions become smaller, with the ratio $\kappa$ / M-B of most lines being shifted closer to unity, when compared to the previous figure.

Finally, the results at $U$=1.8 are shown in Fig. 4 where most line ratios are predicted to be similar for both distributions, although there are some slight enhancements when assuming $\kappa$ distributions with low gas metallicity and $\kappa$=5 (e.g. [NII]$\lambda$1222 $\mu$m, [OII]$\lambda$63, [NeII]$\lambda$12.8 $\mu$m). [OIV]$\lambda$26 $\mu$m is also slightly enhanced but in this case only for higher metallicities.

In summary, assuming $\kappa$ distributions of electron energies instead of M-B distributions moves the IR line fluxes to lower values, except for a small parameter space at low metallicities and with high ionization parameter. Except within a small parameter space with high $U$ (e.g. $U$=1.8), the predicted flux ratios are in the range $0.5 \leq \kappa$ / M-B <1 for the majority of IR lines and model parameters.

### 4.2 Optical emission lines

The effect of $\kappa$ distributions on the emission spectra of optical lines is complex. It depends on both metallicity and ionization parameter. Fig. 5 shows the predictions for $U$=1×10^{-4}. At low metallicities, $Z \approx Z_\odot$, the predictions from models assuming M-B distributions exceed the flux predictions from $\kappa$ models (this is $\kappa$ / M-B < 1) for all the lines considered except H$\beta$, which is very similar for all distributions independently of the metallicity. As the metallicity increases, the line fluxes predicted by $\kappa$ distributions increase slightly ($\kappa$ / M-B > 1), however the only flux that gets significantly higher when using $\kappa$ models is [OIII]$\lambda$4363. For this ionization parameter ($U$=1×10^{-4}), a large deviation from equilibrium, i.e., a $\kappa$=5 distribution, $\kappa$ / M-B becomes smaller than 1 for almost all lines considered, with the exception of [OIII]$\lambda$4363 at high metallicity ($Z_\odot$).

In Fig. 6 the $\kappa$ / M-B predictions for $U$=0.01 are presented. In general, optical line fluxes are not enhanced when assuming $\kappa$ distributions, with the exception of H$\beta$. The maximum H$\beta$ / H$\beta_{M-B}$ is 1.5, reached for $\kappa$ / M-B = 1.5. Increasing the metallicity shifts most line fluxes predicted by $\kappa$ distributions closer to the fluxes predicted by a Maxwellian.

The $\kappa$ / M-B line ratios for $U$=1.8 are presented in Fig. 7. In line with the previous results, the predictions from M-B exceed or are very similar to the predictions from $\kappa$ models for most line ratios (this is, $\kappa$ / M-B < 1). The only exception is [OIII]$\lambda$4363, for which the increase is >1 when $Z \approx Z_\odot$.

The impact of $\kappa$ distributions depends on the metallicity: as the metallicity increases, $\kappa$ / M-B approaches 1.

### 4.3 UV emission lines

In general, when using $\kappa$ distributions the UV emission line fluxes are enhanced ($\kappa$ / M-B > 1) for a wide range of ionization and metallicity parameters. This is primarily due to the fact that the $\kappa$ distributions place relatively more electrons at energies capable of exciting the UV lines, compared to the M-B distribution.

Fig. 8 shows the predictions for $U$=1×10^{-4}. In comparison with a M-B distribution, $\kappa$ distributions have high-energy tails, thus lines with high excitation energies will be enhanced when $\kappa$ distributions are assumed. This is particularly obvious for the UV lines with the highest excitation energies. The CIII$\lambda$977 Å line which has an excitation energy of 12.3 eV, is strongly enhanced by the high-energy tail of $\kappa$ distributions (see Fig. 1). Similar results are obtained for [NIII]$\lambda$991 Å which has an excitation energy of 12.6 eV.

The CIII$\lambda$977 and NIII$\lambda$989 line fluxes are enhanced for $\kappa$ distributions for all metallicities considered. As the metallicity increases, $\kappa$ / M-B > 1 for an increasing number of lines.

Fig. 9 shows the predictions for $U$=0.01. As the ionization parameter increases, the magnitude of the enhancement when assuming $\kappa$ distributions diminishes. This is clearly seen in the calculated fluxes of CIII$\lambda$977 and NIII$\lambda$989, which are still enhanced for all metallicities, but the enhancement is much smaller. The other line fluxes also become less enhanced with increasing ionization parameter. They eventually reach at a turnover point and then the enhancement becomes gradually stronger as can be seen in Fig. 10. This turnover ionization parameter depends on the chosen electron energy distribution and on the emission line in question. For constant ionization parameter, as the metallicity increases we see increases in line fluxes when using $\kappa$ distributions.

Fig. 10 shows the predictions for $U$=1.8. At this value of $U$, the impact of $\kappa$ distributions is strongly dependent on the gas metallicity. For low metallicities no line fluxes show enhancements when $\kappa$ distributions are used, and as the metallicity increases UV lines become enhanced. Almost all ratios are enhanced ($\kappa$ / M-B > 1) for $\kappa$ distributions when $Z\approx 3Z_\odot$.

Although HI Ly$\alpha$$\lambda$1216 is often the most luminous of the UV emission lines, we omitted it from our analysis because it can be strongly affected by the presence of young stars (Villar-Martín et al. 2007), resonance scattering effects (Villar-Martín et al. 1996), and contamination by OV$\lambda$1213.8,1218.3 emission (Humphrey 2019). These effects make the line unreliable for quantitative analyses of the kind performed herein.

### 5 COMPARISON WITH OBSERVED LINE RATIOS

It is interesting to investigate whether observed emission line ratios measured in the emission line regions of AGN are better reproduced using a M-B distribution or a $\kappa$ distribution. In the following figures, the predictions of the photoionization models described in Section 3 are compared with observed emission line ratios. The data was compiled from Solórzano-Iñarrea et al. (2004), Vernet et al. (2001), Humphrey et al. (2008) and Silva et al. (2018) and Silva et al. (2020). It consists in 15 high-z radio galaxies (HizRGs), and two Seyfert galaxies, NGC 1068 (Kraemer et al. 1998), NGC 3393 (Diaz et al. 1988) and 126 Type 2 quasars (QSO2s). The original Type 2 quasar sample had 144 galaxies but we excluded objects where less than 3 lines were observed.

The diagnostic diagrams are shown in Figs. 11 - 15. Different models are represented using different colors and patterns. The lines represent sequences of ionization parameter, from $U$=1×10^{-3} to
\( \alpha = -1, n_H = 100 \text{ cm}^{-3}, U = 10^{-4} \)

**Figure 2.** Ratios of model fluxes for \( \kappa \) and M-B electron energy distributions, for key nebular lines, arranged in order of increasing energy for \( U = 1 \times 10^{-4} \). Each panel corresponds to a different assumption about gas metallicity. Each marker corresponds to a different \( \kappa \) distribution. The grey dotted vertical line shows the position where \( \kappa / \text{M-B} = 0.5 \).

\( \alpha = -1, n_H = 100 \text{ cm}^{-3}, U = 0.01 \)

**Figure 3.** Same as Fig. 2 for \( U = 0.01 \).

\( U = 1.8 \), computed assuming a different distribution of electron energies. To make visualization easier, in the figures we show \( U = 1 \times 10^{-3} \) as the lowest ionization parameter because as we will see in Section 5.1, \( U = 1 \times 10^{-4} \) is too low to reproduce the observed line ratios. For the same reason we will show figures for a power-law index of -1.

The black line represents models computed for a M-B distribution, the blue dashed line represents a \( \kappa \) distribution with \( \kappa = 5 \), the red line represents a \( \kappa \) distribution with \( \kappa = 10 \), magenta shows a \( \kappa \) distribution with \( \kappa = 20 \) and a green line assumes a \( \kappa \) distribution with \( \kappa = 40 \). Different objects are distinguished by different markers and colours. A solid triangle indicates the lowest ionization parameter (\( U = 1 \times 10^{-3} \)) and a pentagon indicates the highest ionization parameter for each model (\( U = 1.8 \)).

We start by showing predictions of the photoionization models in the standard [OIII] 45007/H\( \beta \) versus [NII] 6584/H\( \alpha \) BPT diagnostic diagram (Baldwin et al. 1981). Only NGC 3393 and a few HzRGs have reported measurements for these lines. At low metallicity (\( Z \leq 0.5Z_\odot \)), the models predict too low [OIII] 45007/H\( \beta \) and [NII] 6584/H\( \alpha \) compared to the observations. The fit improves with increasing metallicity. When compared to the M-B distribution, \( \kappa \) distributions shift the ratios [OIII] 45007/H\( \beta \) and [NII] 6584/H\( \alpha \) towards lower values for a given \( U \).
In Fig. 12 we show the diagnostic diagram NV$_{1240}$/HeII$_{1640}$ vs. NV$_{1240}$/CIV$_{1550}$, often used as an abundance indicator (e.g. Hamann & Ferland 1992, 1993; Villar-Martín et al. 1999a). The shape of the curves is similar for models computed assuming $\kappa$ and M-B distributions. Photoionization models assuming $Z=0.1Z_\odot$ predict NV$_{1240}$/HeII$_{1640}$ ratios that are too low to reproduce any of the observations, independently of the electron energy distribution assumed. As the metallicity increases the predicted NV$_{1240}$/HeII$_{1640}$ and NV$_{1240}$/CIV$_{1550}$ ratios increase. At high metallicity ($Z>3Z_\odot$) the models start to generate line ratios similar to those observed. For the same ionization parameter and $Z>0.5Z_\odot$ $\kappa$ distributions predict higher NV$_{1240}$/HeII$_{1640}$ than a M-B. This is clear for the low end of the ionization parameter sequences.

The diagnostic diagram showing CIV$_{1550}$/HeII$_{1640}$ as a function of CIV$_{1550}$/CIII]$_{1909}$ is presented in Fig. 13. At low gas...
metallicity, and when compared to the M-B distribution, $\kappa$ distributions shift the ratio CIV_1550/HeII_1640 to lower values. This situation reverses as the metallicity increases (and also for $Z=Z_\odot$ and high ionization parameter).

Fig. 14 shows the predictions for the diagnostic diagram CIV_1550/CII_2326 as a function of CIII_1909/CII_2326. Compared to M-B distributions, $\kappa$ distributions predict higher CIII_1909/CII_2326 ratios. The data points lie far from the photoionization model predictions for all the parameter space considered. Compared to M-B distributions $\kappa$ distributions produce a slightly worse fit to the data.

Finally, the temperature diagnostic diagram [OIII]_5007/Hβ vs.
Figure 8. Ratios of model fluxes for \( \kappa \) and M-B electron energy distributions, for key nebular lines, arranged in order of increasing energy for \( U = 1 \times 10^{-4} \). The grey dotted vertical lines mark the positions where \( \kappa / \text{M-B} \) is 0.25, and 2. The dashed line indicates where \( \kappa / \text{M-B} \) is 150. Note that at \( Z = 3Z_\odot \), the ratio for the CII\( \lambda 1337 \) line is not shown, as its flux in the M-B model is too low.

[OIII]\( \lambda 4363 \) to [OIII]\( \lambda 5007 \) is presented in Fig. 15. Only the Seyfert galaxies and some HzRGs have observations for these lines. The predicted [OIII]\( \lambda 4363 \) to [OIII]\( \lambda 5007 \) ratios are too low to reproduce most of the observed line ratios. At high metallicities, \( \kappa = 5 \) distributions produce higher [OIII]\( \lambda 4363 \) to [OIII]\( \lambda 5007 \) than the M-B distributions but the ratio is still low compared to the observations. This is the long standing \( T_k \) problem of active galaxies (e.g., Tadhunter et al. 1989; Binette et al. 1996; Richardson et al. 2014).

5.1 Best fits

A Python code was created in order to find the best fitting model for each galaxy, using a \( \chi^2 \) minimization. The code considers every possible line ratio from the data, and compares it with ratios calculated for the different photoionization models. The result is the best fit for each object. All possible line ratios from lines detected in each galaxy were used. All ratios are given equal weighting.

The parameters of the best-fitting models are shown in Tables 2, 3, 4, 5, 6, 7, and 8. For each object, in the first row we present the best-fitting M-B model, and in the second row the best-fitting \( \kappa \)-distribution model.

To simplify NV, SiIV/OIV, SiII, CII, NIV, CIV, HeII, OIII, NIII, CIII], [NeV], CII, MgII, [ArIV], [Ni], [OII], [ArIII] refer to NV\( \lambda 1240 \), SiIV/OIV\( \lambda 1402 \), SiII\( \lambda 1309 \), CII\( \lambda 1335 \), NIV\( \lambda 1486 \), CIV\( \lambda 1550 \), HeII\( \lambda 1640 \), OIII\( \lambda 1666 \), NIII\( \lambda 1750 \), CIII]\( \lambda 1909 \), [NeV]\( \lambda 2424 \), CII]\( \lambda 2326 \), MgII\( \lambda 2800 \), [ArIV]\( \lambda 4740 \), [Ni]\( \lambda 5200 \), [OII]\( \lambda 6300 \), [ArIII]\( \lambda 7135 \), respectively.

5.1.1 Seyfert 2

In Table 2 the lines used in the minimization for the Seyfert 2 galaxies are presented.

In the case of NGC 1068 the best-fitting \( \kappa \) distribution and the M-B predict similar parameters, \( \alpha = -1 \), \( n_H = 10^4 \) and \( Z = 2Z_\odot \), with the exception of the ionization parameter, which is higher when a \( \kappa \) distribution is assumed (\( U_{M-B} = 0.004 \), \( U_\kappa = 0.01 \)). For the Seyfert galaxy NGC 3393 the situation is different. In this case the best-fitting \( \kappa \) distribution and the M-B predict different parameters with the exception of the gas density which is similar.

5.1.2 HzRGs

Table 3 presents the parameters of the best-fitting photoionization models.

The best fitting distribution varies from object to object. Five HzRGs are best fitted by a M-B distribution, and the other ten objects are best fitted by \( \kappa \) distributions, with varying \( \kappa \) indices (see Fig. 16).

Fig. 17 shows the HzRGs binned according to discrepancy in \( \alpha \) (panel a), \( n_H \) (panel b), Z (panel c) and U (panel d). It shows how distant the \( \kappa \) and M-B parameter predictions are and the fraction of objects in which these discrepancies are found.

In general, the HzRGs are best fitted by photoionization models with \( \alpha = -1 \). The assumption of a \( \kappa \) or M-B distribution has no impact on the inferred spectral index, \( \alpha \), in most HzRGs (14/15 or 93%; Fig. 17, panel a)).
than M-B models. For 12 sources (80%) the M-B model produces identical or higher ionization parameters than M-B models. Large discrepancies in the predicted ionization parameters are observed for 6 different objects, see Fig. 16). Of these, 65 (52%) sources are best fitted by the QSO2s are generally better fitted by a distribution with a spectral index of the ionizing continuum; (4) ionization parameter; (5) metallicity; (6) hydrogen density in cm$^{-3}$; (7) $\chi^2$; (8) lines used in the fitting.

| Object       | EED | $\alpha$ | $U$ | $Z$   | $n_H$ | $\chi^2$ | EL                  |
|--------------|-----|----------|-----|-------|-------|----------|---------------------|
| NGC 1068     | M-B | -1       | 0.004 | $Z_{Z_0}$ | 10$^4$ | 4.2      | NV, [SiIV, OIV], [NIV], [CIV], HeII, [OIII], [NII], [NeIII], [SiIII], [ArIV], [NeV], [SiIII], [MgII], [FeIII], [NIII], [OIII], [FeII], [MgII], [OIII], [FeII], [NIII], [OIII] |
|              | $\kappa=40$ | -1      | 0.0106 | $Z_{Z_0}$ | 10$^4$ | 4.6      | NV, [SiIV, OIV], [NIV], [CIV], HeII, [OIII], [NII], [NeIII], [SiIII], [ArIV], [NeV], [SiIII], [MgII], [FeIII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII] |
| NGC 3393     | M-B | -1.5     | 0.009 | $Z_{Z_0}$ | 100   | 8.1      | NV, [SiIV, OIV], [NIV], [CIV], HeII, [OIII], [NII], [NeIII], [SiIII], [ArIV], [NeV], [SiIII], [MgII], [FeIII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [N III], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [N III], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII], [N III], [OIII], [FeII], [NIII], [OIII], [FeII], [NIII], [OIII], [FeII] |
cm$^{-3}$ and the remaining 25 are best-fitted by a model with $n_H=10^6$ cm$^{-3}$. Deviations in $n_H$ by a factor as large as $\geq 100$ are identified in the remaining 17% of QSO2.

In panel (c) of Fig. 18 the ratio $Z_\alpha / Z_{MB}$ is presented. $\kappa$ models produce identical or higher ($Z_\alpha \geq Z_{MB}$) $Z$ than M-B models in 96% (121/126) of cases. The predicted metallicities are consistent ($Z_\alpha / Z_{MB} = 1$) in 56% of QSO2s. For 25% of objects $\kappa$ models predict metallicities a factor of 1.5 to 2 times higher than M-B models. Large discrepancies ($Z_\alpha / Z_{MB} < 0.5$ or $Z_\alpha / Z_{MB} > 3$) in the predicted metallicities occur for 19 QSO2s (15%).

Panel (d) of Fig. 18 presents the results for the ionization parameter. The values of $U$ predicted by $\kappa$ and M-B models differ in 70% (88/26) of QSO2s. The values predicted by $\kappa$ models are a factor of 1.1 to 2 times higher than $U_{MB}$ in 25% (32/126) of cases. For 37 QSO2s (29%) $\kappa$ models predict a lower ionization parameter than the M-B models. In 25% of these cases, $\kappa$ models predict an ionization parameter that is a factor of 1.1 to 2 times lower than the value.
Figure 12. Diagnostic diagram NV λ1240/HeII λ1640 versus NV λ1240/CIV λ1550. HzRGs are represented by pink stars, QSO2s by gold dots, NGC 1068 by a cyan square and NGC 3393 by a green plus.

Figure 13. Diagnostic diagram CIV λ1550/HeII λ1640 as a function of CIV λ1550/CIII λ1909. Symbols and lines as in Fig. 11.

Figure 14. Diagnostic diagram CIV λ1550/CII λ2326 as a function of CIII λ1909/CII λ2326. Symbols and lines as in Fig. 11. Only one QSO2 has reported CII λ2326 measurements.
Best fit model parameters for the HzRGs, assuming a M-B distribution (first row) and the best fitting κ distribution (second row). (1) Object; (2) electron energy distribution; (3) spectral index of the ionizing continuum; (4) ionization parameter; (5) metallicity; (6) hydrogen density in cm$^{-3}$; (7) χ$^2$; (8) lines used in the fitting.

| Object       | EED | α  | U   | Z    | $n_H$ | χ$^2$ | ELs                                                                 |
|--------------|-----|----|-----|------|-------|-------|----------------------------------------------------------------------|
| TXS 0211-122 | M-B | -1 | 0.003 | $Z_⊙$ | 100   | 24.2  | NV, [SiIV+OIV], [OIII]λ4363, [SII]λ6716,6731, Hβ                   |
|              |     | 10 | 0.004 | $Z_⊙$ | 100   | 19.96 | [OII], [NeV]4656, 4960, [NII]4583, [SII]λ6716,6731, Hβ               |
| MRC 0406-242 | M-B | -1 | 0.0028 | $Z_⊙$ | 100   | 2.2   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
|              |     | 40 | 0.0045 | $Z_⊙$ | 100   | 2.5   | [OIII]λ4960, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ                 |
| PKS 0529-549 | M-B | -1 | 0.003 | $Z_⊙$ | 100   | 2.9   | [OIII]λ4960, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ               |
|              |     | 10 | 0.006 | $Z_⊙$ | 100   | 2.6   | [OIII]λ4960, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ               |
| TXS 0828+193 | M-B | -1 | 0.0045 | 0.5$Z_⊙$ | 10$^4$ | 15.17 | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
|              |     | 5  | 0.005 | 0.5$Z_⊙$ | 100   | 11.48 | [OIII]4960, [OII]3727, [NeV]4342, [OII]λ3369, Hβ              |
| MRC 1138-262 | M-B | -1.5 | 0.002 | $Z_⊙$ | 100 | 0.8   | [OIII]λ4960, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ            |
|              |     | 10 | 0.0008 | $Z_⊙$ | 10$^4$ | 0.7   | [OIII]λ4960, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ          |
| 4C-00.54     | M-B | -1.5 | 0.01 | $Z_⊙$ | 100 | 7.2   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
|              |     | 10 | 0.015 | $Z_⊙$ | 100 | 6.5   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
| USS 1558-003 | M-B | -1 | 0.0035 | $Z_⊙$ | 100 | 5.3   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
|              |     | 10 | 0.005 | $Z_⊙$ | 100 | 3.4   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
| 4C+40.36     | M-B | -1 | 0.0017 | $Z_⊙$ | 10$^4$ | 15.7  | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
|              |     | 10 | 0.003 | $Z_⊙$ | 100 | 11.4  | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
| 4C+23.56     | M-B | -1.5 | 0.0065 | $Z_⊙$ | 100 | 6.6   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
|              |     | 10 | 0.0065 | $Z_⊙$ | 100 | 7.5   | NV, [SiIV+OIV], [OIII]λ5007, Hβ                                    |
| 0850-206     | M-B | -1 | 0.004 | 0.5$Z_⊙$ | 10$^4$ | 4.93  | HeIIλ4640, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ             |
|              |     | 10 | 0.006 | 0.5$Z_⊙$ | 10$^4$ | 5.7   | HeIIλ4640, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ         |
| 1303+091     | M-B | -1 | 0.0035 | $Z_⊙$ | 10$^4$ | 1.8   | CIV, HeIIλ1640, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ   |
|              |     | 10 | 0.0045 | $Z_⊙$ | 10$^4$ | 2.1   | CIV, HeIIλ1640, [OII]λ3727, [NeV]4342, [OII]λ3369, Hβ  |
| 4C+03.24     | M-B | -1 | 0.0065 | 0.5$Z_⊙$ | 10$^4$ | 3.8   | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
|              |     | 10 | 0.0065 | 0.5$Z_⊙$ | 10$^4$ | 1.5   | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
| 0731+438     | M-B | -1 | 0.0045 | 0.5$Z_⊙$ | 10$^4$ | 10.2  | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
|              |     | 10 | 0.0045 | 0.5$Z_⊙$ | 10$^4$ | 9.8   | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
| 4C+48.48     | M-B | -1 | 0.01 | $Z_⊙$ | 100 | 2.44  | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
|              |     | 10 | 0.012 | $Z_⊙$ | 100 | 2.26  | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
| MRC 0943-242 | M-B | -1 | 0.0055 | $Z_⊙$ | 100 | 2.2   | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |
|              |     | 40 | 0.0065 | $Z_⊙$ | 100 | 2.4   | NV, CIV, [OIII]λ4363, CIV, HeIIλ1640                           |

Figure 15. Diagram [OIII]λ5007/Hβ vs. [OIII]λ4363/[OIII]λ5007.

Table 3. Best fit model parameters for the HzRGs, assuming a M-B distribution (first row) and the best fitting κ distribution (second row). (1) Object; (2) electron energy distribution; (3) spectral index of the ionizing continuum; (4) ionization parameter; (5) metallicity; (6) hydrogen density in cm$^{-3}$; (7) χ$^2$; (8) lines used in the fitting.
### Table 4: Best fit model parameters for the QSOs. The first row shows the parameters when a M-B distribution is used and the second row shows the best fitting $k$ distribution and its parameters. (1) Object; (2) electron energy distribution; (3) spectral index of the ionizing continuum; (4) ionization parameter; (5) metallicity; (6) hydrogen density in cm$^{-3}$; (7) $\chi^2$; (8) lines used in the fitting.

| Object     | EED | $k$ | $\alpha$ | $U$ | $Z$  | $n_{HI}$ | $\chi^2$ | ELs                                                                 |
|------------|-----|-----|----------|-----|------|----------|----------|---------------------------------------------------------------------|
| SDSS J011506.65 | M-B | 5   | -1 | 0.0065 | $Z_0$ | 10$^5$ | 22.2   | NV, OI, SiIV+OIV, CIV, HeII, SiIII, CIII                       |
| SDSS J022051.68 | M-B | 5   | -1 | 0.0016 | $Z_0$ | 10$^5$ | 17.5   | NV, OI, SiIV+OIV, CIV, HeII, NiIII, CIII                                |
| SDSS J075119.09 | M-B | 5   | -1 | 0.0065 | $Z_0$ | 10$^5$ | 15.7   | NV, OI, SiIV+OIV, CIV, HeII, CIII                                         |
| SDSS J081950.96 | M-B | 5   | -1 | 0.01  | $Z_0$ | 10$^5$ | 12.1   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, CIII                                |
| SDSS J084005.00 | M-B | 5   | -1 | 0.0058 | $Z_0$ | 10$^5$ | 10.7   | NV, OI, SiIV+OIV, NIV, CIV, HeII, OIII, SiII, CIII                                |
| SDSS J095118.93 | M-B | 5   | -1 | 0.0065 | $Z_0$ | 10$^5$ | 13.2   | NV, OI, SiIV+OIV, CIV, [NeIV]1602, HeII, CIII, [NeIV]2422, MgII                                   |
| SDSS J100250.98 | M-B | 5   | -1 | 0.1136 | $Z_0$ | 10$^5$ | 23.1   | NV, OI, CIV, HeII, OIII                                           |
| SDSS J100916.93 | M-B | 5   | -1 | 0.17  | $Z_0$ | 10$^5$ | 21.6   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, NiIII, CIII                                |
| SDSS J125148.53 | M-B | 5   | -1 | 0.008  | $Z_0$ | 10$^5$ | 19.6   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, NiIII, CIII                                |
| SDSS J135531.46 | M-B | 5   | -1 | 0.009  | $Z_0$ | 10$^5$ | 16.6   | OVI+CII, NV, OI, SiIV+OIV, CIV, [NeIV]1602, HeII, OIII, SiII, CIII                                |
| SDSS J150549.73 | M-B | 5   | -1 | 0.017  | $Z_0$ | 10$^5$ | 13.6   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J160900.01 | M-B | 5   | -1 | 0.009  | $Z_0$ | 10$^5$ | 19.97  | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J161059.96 | M-B | 5   | -1 | 0.0058 | $Z_0$ | 10$^5$ | 19.2   | NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J162812.51 | M-B | 5   | -1 | 0.0045 | $Z_0$ | 10$^5$ | 11.1   | NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J101374.84 | M-B | 5   | -1 | 0.0106 | $Z_0$ | 10$^5$ | 5.7    | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J101407.15 | M-B | 5   | -1 | 0.003  | $Z_0$ | 10$^5$ | 2.9    | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J101500.14 | M-B | 5   | -1 | 0.156  | $Z_0$ | 10$^5$ | 46.1   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J20245.82  | M-B | 5   | -1 | 0.23   | $Z_0$ | 10$^5$ | 0.7    | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J206643.64 | M-B | 5   | -1 | 0.0058 | $Z_0$ | 10$^5$ | 0.003  | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J091301.33 | M-B | 5   | -1.5| 0.138  | $Z_0$ | 10$^5$ | 0.07   | OVI+CII, NV, CIV, CIII                                      |
| SDSS J091025.50 | M-B | 5   | -1 | 0.012  | $Z_0$ | 10$^5$ | 11.6   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J023337.89 | M-B | 5   | -1 | 0.004  | $Z_0$ | 10$^5$ | 9.5    | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J074725.50 | M-B | 5   | -1 | 0.036  | $Z_0$ | 10$^5$ | 0.24   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J080428.80 | M-B | 5   | -1 | 0.008  | $Z_0$ | 10$^5$ | 0.1    | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J080826.02 | M-B | 5   | -1 | 0.00276| $Z_0$ | 10$^5$ | 10.8   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J081812.72 | M-B | 5   | -1 | 0.008  | $Z_0$ | 10$^5$ | 25.5   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J081452.04 | M-B | 5   | -1 | 0.009  | $Z_0$ | 10$^5$ | 21.2   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J082550.58 | M-B | 5   | -1 | 0.136  | $Z_0$ | 10$^5$ | 28.6   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J083246.92 | M-B | 5   | -1 | 0.035  | $Z_0$ | 10$^5$ | 16.01  | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J083851.81 | M-B | 5   | -1 | 0.008  | $Z_0$ | 10$^5$ | 25.8   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J094308.14 | M-B | 5   | -1 | 0.0058 | $Z_0$ | 10$^5$ | 35.02  | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, OIII, NiII, CIII                                |
| SDSS J161059.96 | M-B | 5   | -1 | 0.005  | $Z_0$ | 10$^5$ | 10.9   | OVI+CII, NV, OI, SiIV+OIV, CIV, HeII, CIII                                         |
Table 5. Continuation of Table 4.

| Object               | EED  | α    | U    | Z    | $n_H$ | $\chi^2$ | EL                                                                 |
|----------------------|------|------|------|------|-------|----------|----------------------------------------------------------------------|
| SDSS J004826.45      | M-B  | -1   | 0.0058 | $Z_\odot$ | 10^4 | 20.9     | NV, OI, SiIV+$\lambda$1602, CIV, HeII, OIII, CIII, MgII             |
| SDSS J00210.53       | M-B  | -1   | 0.004 | $Z_\odot$ | 10^4 | 11.9     |                                                                      |
| SDSS J084949.57      | M-B  | -1   | 0.015 | $Z_\odot$ | 100  | 39.6     |                                                                      |
| SDSS J11351.03       | M-B  | -1   | 0.004 | $Z_\odot$ | 10^4 | 13.2     |                                                                      |
| SDSS J11353.78       | M-B  | -1   | 0.016 | $Z_\odot$ | 100  | 18.4     |                                                                      |
| SDSS J114856.13      | M-B  | -1   | 0.0065 | $Z_\odot$ | 10^4 | 21.03    |                                                                      |
| SDSS J115510.34      | M-B  | -1   | 0.0058 | $Z_\odot$ | 10^4 | 16.5     |                                                                      |
| SDSS J140220.18      | M-B  | -1   | 0.004 | $Z_\odot$ | 10^4 | 8.7      |                                                                      |
| SDSS J140625.75      | M-B  | -1   | 0.012 | $Z_\odot$ | 100  | 31.03    |                                                                      |
| SDSS J141114.21      | M-B  | -1   | 0.007 | $Z_\odot$ | 100  | 23.7     |                                                                      |
| SDSS J141853.65      | M-B  | -1   | 0.002 | $Z_\odot$ | 10^4 | 17.7     |                                                                      |
| SDSS J144444.05      | M-B  | -1   | 0.12  | $Z_\odot$ | 10^4 | 2.5      |                                                                      |
| SDSS J151747.00      | M-B  | -1   | 0.0065 | $Z_\odot$ | 10^4 | 2.4      |                                                                      |
| SDSS J151815.55      | M-B  | -1   | 0.0106 | $Z_\odot$ | 10^4 | 10.7     |                                                                      |
| SDSS J152051.00      | M-B  | -1   | 0.0106 | $Z_\odot$ | 100  | 50.3     |                                                                      |
| SDSS J152105.83      | M-B  | -1   | 0.008 | $Z_\odot$ | 10^4 | 2.5      |                                                                      |
| SDSS J150345.59      | M-B  | -1   | 0.37  | $Z_\odot$ | 10^4 | 2.0      |                                                                      |
| SDSS J161343.40      | M-B  | -1   | 0.099 | $Z_\odot$ | 10^4 | 15.5     |                                                                      |
| SDSS J162327.66      | M-B  | -1   | 0.012 | $Z_\odot$ | 10^4 | 22.2     |                                                                      |
| SDSS J165525.54      | M-B  | -1   | 0.009 | $Z_\odot$ | 10^4 | 32.2     |                                                                      |
| SDSS J170558.64      | M-B  | -1   | 0.007 | $Z_\odot$ | 10^4 | 14.1     |                                                                      |
| SDSS J170451.51      | M-B  | -1   | 0.005 | $Z_\odot$ | 10^4 | 12.4     |                                                                      |
| SDSS J220126.11      | M-B  | -1   | 0.0065 | $Z_\odot$ | 10^4 | 25.4     |                                                                      |
| SDSS J220126.11      | M-B  | -1   | 0.0065 | $Z_\odot$ | 10^4 | 19.5     |                                                                      |
| SDSS J223348.09      | M-B  | -1   | 0.0065 | $Z_\odot$ | 10^4 | 19.4     |                                                                      |

Note: EL stands for Excitation Line.
## Table 6. Continuation of Table 4.

| Object          | EED   | $\alpha$ | $U$  | $Z$   | $n_H$ | $\chi^2$ | EL                  |
|-----------------|-------|----------|------|-------|-------|----------|---------------------|
| SDSS J082530.67 | M-B   | -1       | 0.25 | $2Z_0$| $10^{6}$| 0.09     | OV1+CII, NV, CIV, HeII, CII |
| SDSS J100133.85 | M-B   | -1       | 0.3   | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J114542.07 | M-B   | -1       | 0.3   | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J116105.48 | M-B   | -1       | 0.3   | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J004423.20 | M-B   | -1       | 0.22  | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J221601.21 | M-B   | -1       | 0.3   | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J163343.85 | M-B   | -1       | 0.0065 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J115947.86 | M-B   | -1       | 0.156 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J103249.55 | M-B   | -1       | 0.0065 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J091357.87 | M-B   | -1       | 0.2   | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J151544.01 | M-B   | -1       | 0.096 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J161447.97 | M-B   | -1       | 0.046 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J162500.57 | M-B   | -1       | 0.4   | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J122214.45 | M-B   | -1       | 0.156 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J105344.18 | M-B   | -1       | 0.075 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J081257.15 | M-B   | -1       | 0.03  | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J162651.76 | M-B   | -1       | 0.032 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J212055.57 | M-B   | -1       | 0.0065 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J023519.66 | M-B   | -1       | 0.14  | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J024525.95 | M-B   | -1       | 0.05  | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J073851.85 | M-B   | -1       | 0.138 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J025339.00 | M-B   | -1       | 0.096 | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
| SDSS J082920.43 | M-B   | -1       | 0.08  | $2Z_0$| $10^{6}$| 0.2      | OV1+CII, NV, CIV, HeII, CII |
Table 7. Continuation of Table 4.

| Object                  | EED | $\alpha$ | $U$ | $Z$  | $n_H$ | $\chi^2$ | EL                          |
|-------------------------|-----|----------|-----|------|-------|----------|-----------------------------|
| SDSS J095819.35         | M-B | -1       | 0.008 | $Z_0$ | $10^6$ | 8.4      | OVII, CI, NV, CIV, HeII, OIII, SiII, CII |
| SDSS J1101448.79        | M-B | -1       | 0.015 | $Z_0$ | $10^6$ | 8.9      | NEV, NVIII, CIV, HeII, CII  |
| SDSS J112343.01         | M-B | -1       | 0.2   | $Z_0$ | $10^6$ | 0.3      | NV, CIV, HeII, CII          |
| SDSS J114753.09         | M-B | -1       | 0.08  | $0.1Z_0$ | $10^4$ | 1.98     | NV, CIV, CII, MgII          |
| SDSS J125733.12         | M-B | -1       | 0.01  | $0.1Z_0$ | $10^6$ | 0.4      | OVII, CI, NV, CIV, MgII     |
| SDSS J124302.62         | M-B | -1       | 0.0065 | $Z_0$ | $10^4$ | 2.9      | OVII, CI, NV, CIV, MgII     |
| SDSS J135059.32         | M-B | -1       | 0.25  | $3Z_0$ | $10^4$ | 0.3      | NV, CIV, HeII, CII          |
| SDSS J133417.04         | M-B | -1       | 0.1   | $Z_0$ | $10^6$ | 0.3      | NV, CIV, HeII, CII          |
| SDSS J155108.96         | M-B | -1       | 0.009 | $0.5Z_0$ | $10^6$ | 6.0      | OVII, CI, NV, CIV, MgII     |
| SDSS J155725.27         | M-B | -1       | 0.025 | $Z_0$ | $10^6$ | 5.5      | OVII, CI, NV, CIV, MgII     |
| SDSS J160158.53         | M-B | -1       | 0.04  | $Z_0$ | $10^6$ | 5.8      | OVII, CI, NV, CIV, MgII     |
| SDSS J207028.19         | M-B | -1       | 0.0065 | $Z_0$ | $10^6$ | 1.9      | OVII, CI, NV, CIV, MgII     |
| SDSS J083031.86         | M-B | -1       | 0.01  | $0.1Z_0$ | $10^6$ | 2.06     | OVII, CI, NV, CIV, MgII     |
| SDSS J162025.94         | M-B | -1       | 0.0136 | $0.5Z_0$ | $10^6$ | 4.9      | OVII, CI, NV, CIV, MgII     |
| SDSS J162806.01         | M-B | -1       | 0.02  | $0.5Z_0$ | $10^6$ | 5.3      | OVII, CI, NV, CIV, MgII     |
| SDSS J170110.12         | M-B | -1       | 0.02  | $0.5Z_0$ | $10^6$ | 9.1      | OVII, CI, NV, CIV, MgII     |
| SDSS J171908.90         | M-B | -1       | 0.02  | $Z_0$ | $10^6$ | 0.009    | OVII, CI, NV, CIV, HeII, CII |
| SDSS J225607.63         | M-B | -1       | 0.05  | $3Z_0$ | $10^6$ | 0.7      | OVII, CI, NV, CIV, HeII     |
| SDSS J215341.33         | M-B | -1       | 0.05  | $3Z_0$ | $10^6$ | 0.7      | OVII, CI, NV, CIV, HeII     |
| SDSS J213557.35         | M-B | -1       | 0.2   | $Z_0$ | $10^6$ | 0.5      | OVII, CI, NV, CIV, HeII     |
| SDSS J114703.82         | M-B | -1.5      | 0.4   | $Z_0$ | $10^6$ | 1.4      | OVII, CI, NV, CIV, HeII     |
| SDSS J090612.64         | M-B | -1.5      | 0.5   | $Z_0$ | $10^6$ | 1.6      | OVII, CI, NV, CIV, HeII     |
| SDSS J073637.54         | M-B | -1.5      | 0.176 | $Z_0$ | $10^6$ | 1.6      | OVII, CI, NV, CIV, HeII     |
| SDSS J003605.26         | M-B | -1.5      | 0.53  | $Z_0$ | $10^6$ | 0.2      | OVII, CI, NV, CIV, HeII     |
| SDSS J004600.48         | M-B | -1.5      | 0.4   | $Z_0$ | $10^6$ | 2.01     | OVII, CI, NV, CIV, HeII     |
| SDSS J004728.77         | M-B | -1.5      | 0.37  | $Z_0$ | $10^6$ | 2.1      | OVII, CI, NV, CIV, HeII     |
| SDSS J161353.27         | M-B | -1.5      | 0.05  | $Z_0$ | $10^6$ | 5.5      | OVII, CI, NV, CIV, HeII     |
| SDSS J125154.02         | M-B | -1.5      | 0.156 | $Z_0$ | $10^6$ | 0.26     | OVII, CI, NV, CIV, HeII     |
| SDSS J023210.88         | M-B | -1.5      | 0.015 | $Z_0$ | $10^6$ | 8.2      | OVII, CI, NV, CIV, HeII     |
| SDSS J075656.49         | M-B | -1.5      | 0.007 | $Z_0$ | $10^6$ | 21.95    | OVII, CI, NV, CIV, HeII     |
| SDSS J112230.35         | M-B | -1      | 0.108 | $Z_0$ | $10^6$ | 1.6      | OVII, CI, NV, CIV, HeII     |
predicted by the M-B. Large discrepancies (U_\kappa / U_{M-B} <0.5 or U_\kappa / U_{M-B} >2) in the predicted ionization parameter occur for 25 QSO2s (20%).

6 DISCUSSION

Line ratios of infrared, optical and ultraviolet emission lines have been extensively used to study the properties of the gas in the narrow line regions of AGNs. Historically, photoionization models generally adopt a M-B distribution for their electron energies. There are, however, some discrepancies between the results of these models and the observed emission line flux ratios. These discrepancies can sometimes be resolved using \( \kappa \) distributions of electron energies (e.g. Nicholls et al. 2012; Humphrey & Binette 2014; Zhang et al. 2016).

6.1 Impact on NLR chemical abundance estimates

Super-solar metallicities have generally been invoked to explain the emission in the NLR of AGN (e.g. Nagao et al. 2006; Dors et al. 2014). However, lower values have been found by Miglioli et al. (2019) who estimated a subsolar or close to solar metallicity in 89% of their objects. They argued that the discrepancy between their results and the ones from other studies are due to the fact that they measured a larger number of emission lines and used a wider range of free parameters in their model grid, which allows them to explain the enhanced NV emission observed in AGN spectra at z\sim2.

Following Silva et al. (2020) we assumed secondary production of carbon in addition to nitrogen. There are some objects whose best fitting model has sub-solar metallicity (SDSS J081257.15+181916.8, SDSS J001814.72+023258.8, SDSS J020245.82+000848.4), but generally our models predict solar or super-solar metallicities. This is not due to the assumption of secondary production of C; in the case where only primary C production was adopted, the predicted gas metallicities of the objects would be even higher.

The assumption of a \( \kappa \) distribution instead of the M-B distribution alters the inferred metallicity in a significant fraction of objects. In 47% of HzRGs and 44% of QSO2s the \( \kappa \) and M-B models predict different metallicities. In most of these objects, \( \kappa \) models imply 1.5 to 2 times higher metallicities than M-B models. More extreme deviations, by a factor of \( \approx 3 \) are inferred in 15% of the total QSO2 sample.

6.2 Do \( \kappa \)-distributions exist in the NLR?

The physical properties of gaseous nebulae are usually inferred under the assumption that the electrons are in an equilibrium M-B distribution. This is assumed because the energy redistribution through elastic collisions of electrons occurs faster than any other process (e.g. Draine & Kreisch 2018). However, if energetic electrons are injected into the gas continually and sufficiently quickly that the particle distribution does not have time to relax to a classical equilibrium distribution, then \( \kappa \) distributions may arise.

Nicholls et al. (2012) proposed several mechanisms that would be capable of creating and maintaining \( \kappa \) distributions in photoionized regions. These include the injection of a population of energetic electrons by acceleration mechanisms such as magnetic reconnection and development of inertial Alfvén waves, shocks, and the injection of high-energy electrons through the photoionization process. Energetic electrons can be produced by the photoionization of dust (Dopita & Sutherland 2000), and X-ray or EUV photoionization (Shull & van Steenberg 1985; Pettrini & da Silva 1997). AGNs are regions where shocks, winds, and turbulence are known to be present (e.g. Baring 1991; Humphrey et al. 2008, 2010; Zhang et al. 2013; Silva et al. 2018), and these processes may also be sufficient to accelerate particles creating \( \kappa \) distributions of electron energies. Several other processes, which are plausibly associated with AGN activity, may also be responsible for deviations from equilibrium, such as ionization by cosmic rays (Giammanco & Beckman 2005), and dissipative turbulence internal to the gas clouds (Miglioli et al. 2019).

In this work we have found tantalizing evidence for the possi-
ble presence of $\kappa$-distributions in the NLR some AGN, based on the
fact that their emission line ratios are better reproduced by photoion-
ization models that use $\kappa$-distributed EEDs. However, more work is
needed to identify and understand physical processes that could es-

tablish $\kappa$-distributed EEDs in the NLR.

7 CONCLUSIONS

In this work we study how the presence of $\kappa$-distributed electron
energies affects the emission line ratios of photoionized nebulae asso-
ciated with AGN. We also provide best fitting parameters ($Z$, $n_H$,
$\alpha$, and $U$) for both $\kappa$ and M-B models for 143 type 2 AGN: 15 HzRG,
126 QSO2s and 2 Seyfert galaxies.

We find that the choice of EED can have a large impact on some
UV and optical emission lines, and that the impact of adopting a $\kappa$
distribution is strongly dependent on gas metallicity and ionization
parameter. The fluxes of UV lines with high excitation energies (e.g.
CIII $\lambda$4977, NV $\lambda$1240) are greatly enhanced by $\kappa$ distributions. The
enhancement is stronger when the deviation from thermal equilib-
rium is large, i.e. for lower values of $\kappa$.

In the optical, some line fluxes are enhanced when $\kappa$ distributions
are adopted (e.g. [OIII]$\lambda$4363), but in most cases the line fluxes are
fainter in the $\kappa$ models compared to the M-B models ($\kappa / M-B < 1$).

Using $\kappa$ distributions results, generally, in a decrease of the predicted
IR line fluxes. With increasing metallicity and ionization parameter

the differences between ratios obtained using M-B distributions and
$\kappa$ distributions becomes smaller.

We have compared our models against the rest-frame UV to opti-
cal emission line ratios of 143 type 2 active galaxies. We found that
for a subset of the sources (one of the two studied Seyfert galaxies,
67% of HzRGs and 69% of QSO2s) a photoionization model using
$\kappa$-distributed electron energies provides a significantly better fit to
the data, which suggests that $\kappa$-distributed electron energy distribu-
tions may indeed be present in the NLR of some type 2 AGN.

The assumption of a $\kappa$ or M-B distribution has no impact on the
inferred spectral index, $\alpha$ in most HzRGs (14/15 or 93%) QSO2s
(116/126 or 92%).

The assumption of a $\kappa$ distribution instead of the M-B distribution
has no impact on the derived gas density in most HzRG (11/15 or
73%) and QSO2s (104/126 or 83%). Deviations in $n_H$ by a factor as
large as $\geq 100$ are identified in the remaining 17% of QSO2s.

Regarding the metallicity, the general trend in both HzRGs and
QSO2s is that $\kappa$ models produce identical (roughly in half of both
samples) or higher Z than M-B models. More specifically, the
predicted metallicities are consistent ($Z_k = Z_{M-B}$) in 53% of HzRGs
(8/15) and 56% of QSO2s (71/126). For the rest of both samples,
but for a few exceptions, $\kappa$ models produce 1.5 to 2 times higher Z
than M-B models in 40% HzRG (6/15) and 25% (32/126) QSO2s.

The predicted $U$ values for the $\kappa$ and M-B models differ in most

Figure 17. HzRGs binned according to discrepancy in (a) $\alpha$, (b) $n_H$, (c) $Z$, and (d) $U$ between $\kappa$ and M-B distributions.
Figure 18. QSO2s binned according to discrepancy in (a) $\alpha$, (b) $n_H$, (c) $Z$, and (d) $U$ between $\kappa$ and M-B distributions.

objects (13/15 or 87% of HzRG and 88/126 or 70% of QSO2). HzRGs and QSO2s behave differently in the sense that in general $\kappa$ models produce higher $U$ values ($1.1 < U_\kappa / U_{M-B} < 2$), while the relative factor $U_\kappa / U_{M-B}$ is more evenly spread in QSO2s at both sides of $U_\kappa / U_{M-B} = 1$. Large discrepancies occur for 25 QSO2s (20%, all of which have $U_\kappa / U_{M-B} > 2$) and one HzRG (with $U_\kappa / U_{M-B} < 0.5$).

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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