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A review of diagnostic emission line ratios in the Narrow Line Region of Active Galactic Nuclei

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The availability of new observing facilities both from ground and space such as the Keck 10m telescope and the Hubble Space Telescope is casting new light on the spectroscopic investigation of emission line galaxies. In particular, it is now possible to detect spectra with a significantly improved signal to noise ratio in a very wide wavelength range, from the ultraviolet to the near infrared (HST, Keck) and beyond (ISO is unveiling the far infrared domain). As we move to high redshifts, however, it is more likely that the observed spectra are given by the contribution of different components in the galaxy: in particular, this may be the case if an Active Galactic Nucleus (AGN hereafter) emitting a power-law continuum is surrounded by regions with strong star formation activity. The identification of the source which ionizes the line emitting regions is then complicated by the fact that we are observing the integrated spectrum from regions which are ionized by different sources. In this paper we wish to review which line ratios may be used in order to discriminate between photoionization by young stars and power-law continuum in the wavelength range from 1200 Å to 100 μm. To this aim we used the photoionization code Cloudy (Ferland 1996) to present a series of diagnostic diagrams showing the dependence of emission line ratios on the main input parameters of photoionization models in the case of one component models with gaseous clouds ionized by (1) a stellar continuum typical of an HII region and (2) a power-law continuum typical of an AGN: these line ratios are plotted as isoratio maps for different values of the hydrogen density, ionization parameter and slope of the power-law continuum. We then show how the results may be affected by more realistic assumptions about the environment of the ionized gas: to this aim, we show the effects on selected line ratios of (a) the presence of two populations of clouds with different densities and (b) an AGN surrounded by regions with strong star formation activity.

Key words: AGN: spectra – narrow line region – emission line ratios

1. Introduction

It is well known that photoionization models computed assuming a *single* population of clouds with a given density and distance from the ionizing source are *not* adequate to fit in detail the emission line ratios observed in AGNs. In fact, single-component models in most cases do not provide a satisfactory fit of the observed emission line ratios, in particular when lines with very different ionization potentials or critical densities are considered. A discussion of multi-component photoionization models of Seyfert 2 galaxies has been recently given by Komossa and Schulz (1997); Ferguson et alii (1997) show how the integrated narrow-line spectrum in AGNs can be predicted by the integration of an ensemble of clouds. We shall not discuss the inner line emitting regions of AGNs, the so-called Broad Line Region (see e.g. Radovich and Rafanelli (1994) and references therein).

However, in some cases a detailed modeling of the physical parameters which produce the observed emission line spectrum is not required: what is needed is a simple way to identify the most likely ionizing source, namely

Fig. 1: Ionization potentials of the first ten stages of He, C, N, O, Ne, S, Mg and Si (data from Ferland 1996). The dashed line shows the boundary of 70 eV between young stars and a power-law continuum.

to discriminate between ionization from stars and an AGN. An example is given by the spectroscopic analysis of samples of galaxies selected by the emission in some spectral band (see e.g. Boyle et al. 1995, Schmidt et al. 1997 for spectroscopy of X-ray selected galaxies). For this reason, we give here a review of which emission line ratios may be used in order to: (1) discriminate between ionization by a stellar and a power-law continuum in a wide spectral range (1200Å - 100 μ m) for different values of the model input parameters (spectral index, hydrogen density and ionization parameter); (2) have a first-order estimate of the main physical parameters (density and ionization parameter) derived from different line ratios.

Line ratios were computed using the Gary Ferland's photoionization code Cloudy (Ferland 1996). They are plotted as isoratio maps for different values of the hydrogen density ($n_H = 10 - 10^5 \text{ cm}^{-3}$) and ionization parameter ($U = 10^{-4} - 10^{-0.5}$) and for different ionizing continua (stellar continuum models: Mihalas continuum with $T_* = 38000 \text{ K}$; power-law models: power-law continuum, $F_\nu \propto \nu^\alpha$, with $\alpha = -2.0, -1.5, -1.0$). Line ratios are also available in digital form upon request (e-mail: radovich@pd.astro.it).

The paper is organized as follows. We give in §2 a short summary of the criteria which may be used in order to discriminate between ionization from young stars and a power-law. Single-cloud models producing the isoratio maps in the ultraviolet, optical and infrared spectral ranges are discussed in §3. In §4 we discuss some composite models, where we simulate the integrated spectrum observed in the case of an active nucleus with strong circumnuclear star formation regions.

2. General criteria

It is well known that photoionization of line-emitting clouds by young stars and a power-law may be spectroscopically discriminated either looking for emission lines requiring high ionization potentials untypical for HII regions or taking ratios of low ionization lines which are enhanced by the presence of high-energy photons.

The first criterion is based on the fact that usually the presence of photons above 70 eV is negligible in those regions which are ionized by stars; on the other hand, power-law continua in AGN extend well beyond this value. We can therefore assume that lines requiring ionizing potentials higher than 70 eV are most likely produced by a power-law continuum rather than by unusually hot stars ($T_* \gg 40000 \text{ K}$). For comparison, the ionization potentials of the first ten ionization stages of He, C, N, O, Ne, S, Mg and Si are plotted in Fig. 1.

Fig. 2: Line ratios computed in the UV range for: power-law continuum, $\alpha = -1.5$, $\log n_H = 3$ (top) and Mihalas continuum, $T_* = 38\,000\text{K}$, $\log n_H = 2$ (bottom); for each line, boxes show values for $\log U$ from -4.0 (left) to -0.5 (right). Overlaid are the average line ratios taken from Storch-Bergmann et alii (1995), corrected for reddening (see text for details).

The second criterion is also related to the different continuum shape in AGN and HII regions. In the ‘standard’ theory of photoionized gaseous nebulae we may define a sharp boundary, the so-called Strömgren radius (Osterbrock 1989), between the zone where the gas is fully ionized by ultraviolet photons and the zone where ultraviolet photons have been absorbed and the gas is neutral. The ionization structure is somewhat different when X-ray photons are present: in this case a low ionization zone is created beyond the Strömgren radius, where low ionization and neutral atoms coexist with hot free electrons produced by the ionization by keV photons of neutral hydrogen atoms and of the inner shells of heavy elements. The main line emission mechanism is therefore given here by collisional excitation of neutral or low ionization atoms: it follows that high ionization lines produced in the inner regions ionized by UV photons may coexist with low ionization lines produced in these outer regions.

In both cases, the intensities of the emission lines are strongly dependent on the ionizing flux. This is usually parameterized by the dimensionless ionization parameter, defined as $U = Q_H / (4\pi R^2 n_H c)$. Q_H is the number of hydrogen ionizing photons, n_H the hydrogen density, R the distance between the ionizing source and the inner side of the cloud. In fact, in AGN also high ionization lines may be too weak to be observed if the ionization parameter is low; on the other hand, the ratio of lines enhanced in the partially ionized zone and lines formed in inner parts of the cloud decreases as we go to higher values of the ionization parameter. It follows that an independent indication on the ionization parameter is required. In their well known diagnostic diagrams, Baldwin et alii (1981, BPT hereafter) and Veilleux and Osterbrock (1987, VO) chose the $[\text{OIII}] \lambda 5007 / \text{H}\beta$ ratio as an indicator of the ionization parameter, and plotted it versus the $[\text{OIII}] \lambda 5007 / [\text{OII}] \lambda 3727$ (BPT), $[\text{OI}] \lambda 6300 / \text{H}\alpha$, $[\text{SII}] \lambda 6724 / \text{H}\alpha$ ¹ and $[\text{NII}] \lambda 6583 / \text{H}\alpha$ (VO) ratios. The advantage of this approach is that (1) the chosen ratios discriminate very well between young stars and power-law photoionization and (2) in the case of the VO diagrams, they are not sensitive to dust reddening.

As the determination of the ionization parameters and density of the line emitting clouds is concerned, the most useful line ratios are of course those where small changes in one of these parameters produce as large as possible changes in the value of the ratio, whereas they are as independent as possible on the other one.

¹We indicate as $[\text{SII}] \lambda 6724$ the sum of the $[\text{SII}] \lambda\lambda 6716, 6731$ lines.

3. Single-cloud models

3.1. Parameters of the models

The photoionization models were computed using the latest release of Gary Ferland's photoionization code Cloudy 90 (Ferland 1996). For the AGN models we assumed as the continuum a power-law ($F_\nu \propto \nu^\alpha$, $\alpha = -2.0, -1.5, -1.0$) with cutoffs at low ($\lambda = 10\mu\text{m}$, $\alpha = 2.5$) and high ($h\nu = 50\text{keV}$, $\alpha = -2$) energies.

In the HII-region case (photoionization by stars), we considered a non-LTE Mihalas (1972) stellar continuum ($\log g = 4$); a 'standard' value of the stellar temperature was chosen, $T_{\text{eff}} = 38\,000\text{ K}$.

The ionization parameter was varied between $\log U = -4.0$ and $\log U = -0.5$ with an increment $\Delta \log U = 0.5$. The hydrogen density was varied between $n_{\text{H}} = 10$ and $n_{\text{H}} = 10^5\text{ cm}^{-3}$ with an increment $\Delta \log n_{\text{H}} = 1$.

In all models, abundances were fixed to the 'standard' solar composition (Grevesse and Anders 1989, Grevesse and Noels 1993) as given by Ferland (1996), namely:

H: 1.00, He: 1.00×10^{-1} , Li: 2.04×10^{-9} , Be: 2.63×10^{-11} , B: 7.59×10^{-10} , C: 3.55×10^{-4} , N: 9.33×10^{-5} , O: 7.41×10^{-4} , F: 3.02×10^{-8} , Ne: 1.17×10^{-4} , Na: 2.06×10^{-6} , Mg: 3.80×10^{-5} , Al: 2.95×10^{-6} , Si: 3.55×10^{-5} , P: 3.73×10^{-7} , S: 1.62×10^{-5} , Cl: 1.88×10^{-7} , Ar: 3.98×10^{-6} , K: 1.35×10^{-7} , Ca: 2.29×10^{-6} , Sc: 1.58×10^{-9} , Ti: 1.10×10^{-7} , V: 1.05×10^{-8} , Cr: 4.84×10^{-7} , Mn: 3.42×10^{-7} , Fe: 3.24×10^{-5} , Co: 8.32×10^{-8} , Ni: 1.76×10^{-6} , Cu: 1.87×10^{-8} , Zn: 4.52×10^{-8} .

The geometrical thickness was set stopping the integration when the temperature fell below $T_e = 3000\text{ K}$.

As a first step, we defined three spectral ranges (ultraviolet: $1200\text{\AA} - 3500\text{\AA}$; optical: $3500\text{\AA} - 9000\text{\AA}$; infrared: $1\mu\text{m} - 100\mu\text{m}$) and for each of them we plotted in Fig. 2-4 the ratios $F(\lambda)/F(H\beta)$ of the brightest lines in 'typical' HII region (Mihalas continuum, $T_* = 38\,000\text{ K}$, $\log n_{\text{H}} = 2$) and AGN (power law with $\alpha = -1.5$, $\log n_{\text{H}} = 3$) conditions, for different values of the ionization parameter.

We took as comparison the line ratios given by Storchi-Bergmann et al. (1995) for a sample of 48 southern star-forming and Seyfert galaxies. They are well suited for a comparison with our models since they are given in a broad spectral range (from $1200\text{ \AA}$ to $10,000\text{ \AA}$) and the spectra in the optical have been taken matching the IUE aperture ($10'' \times 20''$), which is large enough to simulate the observation of the integrated spectrum from a high redshift galaxy. We first computed the average line ratios for Seyfert 2 and HII galaxies and then corrected for reddening assuming $H\alpha/H\beta = 2.8$ and 3.1 for HII and Seyfert galaxies respectively, $\text{Ly}\alpha/H\beta = 25$ (Osterbrock 1989). In the infrared, we took as comparison the near-IR and ISO SWS ($2.5\text{--}40\mu\text{m}$) line fluxes given by Oliva et al. (1994) and Moorwood et al. (1996) for the Circinus galaxy (AGN case) and by Rigopolou et al. (1996) for the starburst NGC 3256 (HII-region case). It may be seen from Fig. 2-4 that, with some exceptions (i.e. [NeIV] $\lambda 2424$ for AGN, UV lines for star-forming galaxies where however available data are poor, [NeII] $\lambda 12.8\mu\text{m}$, [SIII] $\lambda 34\mu\text{m}$ and [SiII] $\lambda 35\mu\text{m}$ in the AGN plot) the agreement between models and observed ratios is quite good: we conclude that *single-component models with the above parameters give at least a first-order fit of most of the observed line ratios even in large aperture spectra*.

Starting from these plots, we then isolated those line ratios which are most useful in order to (1) detect the presence of an AGN and (2) determine the physical parameters of the cloud. To this aim we plotted these ratios as isoratio maps for different values of the hydrogen density and ionization parameter, both for a given stellar temperature ($T_* = 38\,000\text{ K}$, Fig. 5-7) as comparison and a power-law continuum with $\alpha = -2.0$ (Fig. 8-10), $\alpha = -1.5$ (Fig. 11-13) and $\alpha = -1.0$ (Fig. 14-16).

In the isoratio maps, line ratios useful to determine the ionization parameter are those with contours running parallel to the x-axis (hydrogen density); conversely, the ratios useful to determine the density are those with contours parallel to the y-axis (ionization parameter); in most cases, the behavior is intermediate, that is the ratio depends on both parameters.

3.2. Ultraviolet range (1200-3500 Å)

This spectral range is rich of high ionization lines (ionization potential above 70 eV), which are not produced in typical HII region conditions. Their intensity is however strongly dependent on the ionization parameter and if their presence is clearly indicative of the presence of an AGN, their absence does not mean that the ionization is by stars. Moreover, we should always be aware that the extinction by dust around the nuclear regions may obliterate the UV emission lines.

Ionization source - The most meaningful evidence of a power-law photoionization is of course given by the presence of lines requiring ionization energies above 70 eV (see Fig. 1), as [NeV] $\lambda 3346$, [NeV] $\lambda 3426$ ($\chi(\text{NeIV}) = 97\text{ eV}$) and NV $\lambda 1240$ ($\chi(\text{NIV}) = 78\text{ eV}$). [NeV] $\lambda 3426/\text{MgII } \lambda 2798$ and NV $\lambda 1240/\text{CII } \lambda 1335$ ratios between 0.5 and ≥ 5 strongly indicate that the ionization source is by a power-law rather than by stars. Even in the power-law models, these lines are however too weak to be observed when the ionization parameter is low ($\log U \leq -3$). In

Fig. 3: Line ratios computed in the optical range. Symbols as in Fig. 2.

this case, lines of ‘intermediate’ ionization such as [NeIV] $\lambda 2424$ ($\chi(\text{NeIII}) = 64$ eV), HeII $\lambda 1640$ ($\chi(\text{HeII}) = 55$ eV), OIV] $\lambda 1402$ ($\chi(\text{OIII}) = 55$ eV) and CIV] $\lambda 1549$ ($\chi(\text{CIII}) = 48$ eV) may be used. These lines may be produced by a stellar continuum, but unusual conditions (e.g. very hot stars) are required; in particular, HeII $\lambda 1640/\text{CIII}]$ $\lambda 1909$, if present, is hardly higher than 1 with photoionization by stars, whereas it is expected to vary between 0.5 and ≥ 10 in power-law models. High values (> 10) of the CIV] $\lambda 1549/\text{CIII}]$ $\lambda 1909$ and CIII] $\lambda 1909/\text{CII}]$ $\lambda 1335$ ratios may also be used in principle to infer the presence of a ‘hard’ ($\alpha \sim -1.0$) power-law continuum.

Ionization parameter - The ionization parameter is of course best traced by ratios involving lines from different ionization potentials; as usual, the lines should be close in wavelength in order to minimize effects introduced by dust reddening. The most useful ratio is likely [NeV] $\lambda 3426/[\text{Ne IV}]$ $\lambda 2424$ ($\sim 0-5$), since it depends weakly on both n_{H} and α . Among low ionization lines, the values of CIII] $\lambda 1909/\text{CII}]$ $\lambda 2326$ and MgII $\lambda 2798/\text{CII}]$ $\lambda 2326$ change with the ionization parameter, but are nearly the same in young stars and power-law photoionization models.

Density - The most useful ratios to determine the density are those from lines of the same ion, having the same excitation energy. A list of these doublets in the ultraviolet may be found for example in Dufour (1995). In AGNs, however, these lines are often blended and can’t be used. Ratios from low ionization lines which form in nearly the same region of the cloud, as MgII $\lambda 2798/[\text{OII}]$ $\lambda 2471$ and CIII] $\lambda 1909/\text{CII}]$ $\lambda 1335$, provide a good trace of the density in stellar continuum models since for a given density the dependence on the ionization parameter is weak (contour lines parallel to the y-axis). However, in power-law models low ionization lines are enhanced in the Partially Ionized Zone: line ratios then depend on density, ionization parameter and slope of the continuum. If $\alpha = -1.0$, CIII] $\lambda 1909/\text{CII}]$ $\lambda 1335$ is almost independent of density (the contour lines are now parallel to x-axis); as concerns MgII $\lambda 2798/[\text{OII}]$ $\lambda 2471$, its dependence on density versus ionization parameter is weaker as we move from $\alpha = -2.0$ to $\alpha = -1.0$, in particular when $\log n_{\text{H}} < 3$.

3.3. Optical range (3500-10000 Å)

Ionization source - As noted before, the most useful tool in order to discriminate between young stars and power-law ionization is given by the ratios in the VO diagrams. If [OIII] $\lambda 5007/\text{H}\beta > 10$, we have a high probability that ionization is by a power-law since this value is easily achieved by power-law models for $\log U > -3$ ($\alpha = -1.5$), while in the case of stellar continuum models it would require high values of the ionization parameter ($\log U > -1$) and hydrogen density ($\log n_{\text{H}} \geq 4$), or a high stellar temperature ($T_{\star} > 38\,000$ K). In addition, ionization by a power-law rather than by stars is more likely if [OI] $\lambda 6300/\text{H}\alpha \geq 0.05$, [NII] $\lambda 6583/\text{H}\alpha \geq 0.6$ and [SII] $\lambda\lambda 6716, 6731/\text{H}\alpha \geq 0.5$,

which requires $\log U \leq -3.0$ in those models with $\alpha = -2.0, -1.5$; only in the models with $\alpha = -1.0$ we always have higher values of the VO ratios than in the stellar continuum models. It follows that, unless $\alpha \geq -1.0$, an overlap may occur between the values of these ratios given by low-ionization stellar continuum models and high-ionization power-law models: an indication of the ionization parameter given e.g. by $[\text{OIII}] \lambda 5007/\text{H}\beta$ is then required.

Apart from the classical VO ratios, $[\text{NeIII}] \lambda 3869/[\text{OII}] \lambda 3727$ may be used to discriminate between AGNs and HII regions when it is > 1 . This occurs both in stellar and power-law continuum models for high values of the ionization parameters and/or hydrogen densities; however, for a typical density $\log n_{\text{H}} = 3$ in order to obtain $[\text{NeIII}]/[\text{OII}] > 1$ we must have $\log U \geq -1.5$ (or higher densities) in stellar continuum models, whereas in power-law models this happens when $\log U \geq -2$ ($\alpha = -1.5$).

The $[\text{NeIII}] \lambda 3869/\text{H}\gamma$ ratio is more meaningful, since it is > 1 in AGN models for a wide range of ionization parameters (see Fig. 3) and hydrogen densities, whereas the opposite is true for stellar continuum models; however, the presence of Balmer absorption lines from the underlying galaxy often makes it difficult to have a reliable estimate of the $\text{H}\gamma$ intensity.

The $[\text{OIII}] \lambda 5007/[\text{OII}] \lambda 3727$ (BPT) ratio does not discriminate very clearly between stellar continuum and power-law ionization, since there is a considerable overlap between the values given by the models, even if it is somewhat more likely to have higher values (e.g. $[\text{OIII}] \lambda 5007/[\text{OII}] \lambda 3727 > 5$) in power-law than stellar continuum models. Besides, this ratio strongly depends on the dust reddening since the two lines are not close in wavelength.

Osterbrock et alii (1992) showed that the ratio $[\text{OII}] \lambda 7325/\text{H}\alpha$ and $[\text{SIII}] \lambda \lambda 9069, 9531/\text{H}\alpha$ (but in this case we have a greater overlap between power-law and stellar continuum models) may also be used to discriminate between photoionization by stars and a power-law in a similar way as for the VO ratios, namely higher values (e.g. > 0.03 and > 0.7 respectively) are expected in power-law than in stellar continuum models for low ionization parameters or hard continua.

Ionization parameter - As already discussed above, the most useful indicators of the ionization parameter are the $[\text{NeIII}] \lambda 3869/[\text{OII}] \lambda 3727$ and $[\text{OIII}] \lambda 5007/\text{H}\beta$ ratios. At longer wavelengths an indication of the ionization parameter may be obtained from the $[\text{SIII}] \lambda \lambda 9069, 9531/[\text{SII}] \lambda \lambda 6716, 6731$ ratio.

In the short-wavelength range, the $[\text{NeV}] \lambda 3426/[\text{OII}] \lambda 3727$ ratio may also be used to derive the ionization parameter: in fact, this ratio is quite independent of density and may be used to derive the ionization parameter in the single-component assumption (but see later §4).

Density - The most useful density indicator is of course given by the $[\text{SII}] \lambda 6731/[\text{SII}] \lambda 6716$ ratio (Osterbrock 1989). $[\text{OIII}] \lambda 4363/[\text{OIII}] \lambda 5007$ gives the electron temperature, but it is well known (Osterbrock 1989) that the critical density for collisional de-excitation is higher for $[\text{OIII}] \lambda 4363$ ($n_{\text{e}} = 7 \times 10^5 \text{ cm}^{-3}$) than for $[\text{OIII}] \lambda 5007$ ($n_{\text{e}} = 4 \times 10^3 \text{ cm}^{-3}$). Values of this ratio implying abnormally high electron temperatures ($T_{\text{e}} \gg 20\,000 \text{ K}$) may be therefore explained with the presence of a high density component ($n_{\text{e}} \leq 10^6 \text{ cm}^{-3}$).

3.4. Infrared range (1-100 μm)

Fine-structure lines in the far infrared provide a tool of primary importance in the investigation of the properties of the emitting regions due to (1) the low sensitivity to extinction by dust and (2) the availability of lines in a wide range of ionization potentials (e.g.: $[\text{NeII}] \lambda 12.8 \mu\text{m}$ and $[\text{NeV}] \lambda 24.2 \mu\text{m}$). A thorough analysis of diagnostic diagrams built starting from fine-structure line ratios was given by Spinoglio and Malkan (1992), Voit (1992) and Dinerstein (1995): we defer to these papers for more details.

Ionization source - High ionization lines which are not typical of HII regions are $[\text{SiVI}] \lambda 1.96$ ($\chi(\text{SiV}) = 167 \text{ eV}$), $[\text{NeV}] \lambda 24.2$ ($\chi(\text{NeIV}) = 97 \text{ eV}$), $[\text{MgV}] \lambda 5.6$ ($\chi(\text{MgIV}) = 109 \text{ eV}$). $[\text{OIV}] \lambda 26$ ($\chi(\text{OIII}) = 55 \text{ eV}$) may be produced with photoionization by stars, but it is usually weak. According to Spinoglio and Malkan (1992), a $[\text{SIV}] \lambda 10.5/[\text{NeII}] \lambda 12.8 < 1$ ratio is more indicative of photoionization by stars rather than by a power-law. In our models, in both cases this ratio is > 1 above $\log U \sim -2.5$ and steeply decreasing for lower values of the ionization parameter. It follows that from this ratio alone it is not possible to discriminate between young stars and power-law ionization; nevertheless, as pointed out by Spinoglio and Malkan (1992) a strong $[\text{NeII}] \lambda 12.8$ emission if compared to $[\text{SIV}] \lambda 10.5$ is more likely to occur in the case of photoionization by stars. The $[\text{OI}] \lambda 63/[\text{NIII}] \lambda 57$ ratio is also useful in order to discriminate between stellar and power-law ionization, since $[\text{OI}] \lambda 63$ is collisionally enhanced in the Partially Ionized Zone. In stellar continuum models high values of density and/or low values of the ionization parameter are needed in order to obtain a ratio higher than 1, whereas this is more typical of power-law models, in particular when $\alpha \sim -1.0$. Voit (1992) showed that $[\text{NeII}] \lambda 12.8/[\text{NeIII}] \lambda 15.6$ discriminates between hard ($\alpha = -1.0$) and soft ($\alpha = -2.0$) power-law continua for a given value of the ionization parameter.

Ionization parameter - The ratios $[\text{NeV}] \lambda 14.3/[\text{NeIII}] \lambda 15.6$ (Voit 1992), $[\text{SIV}] \lambda 10.5/[\text{NeII}] \lambda 12.8$, $[\text{SIV}] \lambda 10.5/[\text{SIII}] \lambda 35$ and $[\text{OIII}] \lambda 52/[\text{SIII}] \lambda 34$ (Spinoglio and Malkan 1992) vary strongly with the ionization parameter.

Density - The most useful ratios in order to determine the density of the gas are (Spinoglio and Malkan 1992, Dinerstein 1995) $[\text{SIII}] \lambda 18.7/[\text{SIII}] \lambda 34$ and $[\text{OIII}] \lambda 52/[\text{OIII}] \lambda 88$, since they are fairly independent on the

Fig. 4: Line ratios computed in the infrared range. Symbols as in Fig. 2, but the observed ratios are those given in literature for the Circinus and NGC 3256 galaxies (see text for references).

ionization source. $[\text{ArIII}] \lambda 9 / [\text{SiIII}] \lambda 34$ may be also used, with the exception, for $\alpha = -1.0$, of the region $\log n_{\text{H}} < 3$ where the dependence on density is very weak.

4. Multi-component models

In order to show how the presence of different components of ionizing radiation may affect the observed line ratios, we now consider the following models:

- Multi-density models: different line ratios are produced in clouds with different densities. This has been shown to be the case in the Narrow Line Region of Seyfert galaxies by Komossa and Schulz (1997) and Ferguson et al. (1997); since a detailed discussion has been already given by these authors, some indicative results will only be given here.
- Hybrid models: we consider the presence of both young stars and a power-law as ionization sources, as it may happen when we observe the integrated spectrum of an active nucleus surrounded by circumnuclear star forming regions (see e.g. Radovich et al. [1996, 1997, 1998]).

Line fluxes in these multi-component models were computed as follows. We first defined for each component an *effective* distance from the nucleus:

$$R_{\text{eff}} = \epsilon^{0.5} R, \quad (1)$$

where ϵ is the covering factor of the clouds in each component, R the distance of the clouds from the nucleus.

We then took for each line the fluxes $F_i(\lambda)$ given as output by Cloudy in the i th component, and computed the total flux in an N-component model as in Radovich and Rafanelli (1994), namely (normalized to $\text{H}\beta$):

$$\mathcal{R}_{\text{tot}} = \frac{\sum_1^N \chi_i^2 F_i(\lambda)}{\sum_1^N \chi_i^2 F_i(\text{H}\beta)}, \quad (2)$$

$$\chi_i = \frac{R_{\text{eff}}(i)}{R_{\text{eff}}(1)}, \quad i = 2, \dots, N.$$

The χ parameter may be also interpreted as the weight assigned to the different components.

We did not consider the effect of dust, either mixed with the gas or located in front of it, which may of course obliterate the contribute from each component, in particular as we move to short wavelengths.

Multi-density models - The effects of density stratification on photoionization models of the Narrow Line Region in Seyfert galaxies have already been discussed in detail elsewhere (Komossa and Schulz 1997, Ferguson et al. 1997). In particular, Ferguson et alii (1997) adopted the so-called Locally Optimally Emitting Clouds (LOC) hypothesis, namely they considered an ensemble of clouds with different physical parameters, where we observe lines from the clouds best able to emit them. This assumption is necessary in most cases to fit narrow-line spectra, in particular when both low ionization (e.g. [OIII] $\lambda 5007/H\beta \leq 10$) and high ionization (e.g. [NeV] $\lambda 3426/H\beta \sim 1$) features are present (see also Radovich et al. 1998).

In order to show what happens when a multi-density model is considered instead of a single-component one, we considered the following simple case. We computed the line fluxes from two models with the following input parameters: $\alpha = -1.5$ and (1) $\log n_H = 5$, $\log U = -1$ (high-density component) and (2) $\log n_H = 3$, $\log U = -3$ (low-density component). We then put $\epsilon_1 = \epsilon_2$ in eq. 1; given the assumption that both components are ionized by the same number of ionizing photons, that is in absence of internal absorption, it follows from the definition of the ionization parameter that $\chi^2 = (R_2/R_1)^2 = (Un_H)_1/(Un_H)_2$, whence $\chi = 100$. Selected line ratios given as output by this model are shown in Fig. 17. The main result is that high ionization lines such as CIV $\lambda 1549$ and [NeV] $\lambda 3426$ are considerably enhanced if compared with the values given by single-cloud, low-density models (see e.g. CIV $\lambda 1549$ /CIII] $\lambda 1909$); it follows that the ionization parameter indicated by these ratios is higher ($\log U \geq -2.0$) than that indicated by ratios involving low ionization lines ($\log U \leq -2.0$).

Hybrid models - We extracted from the discussion of §2 two 'test' models, namely (1) an AGN component, $n_H = 10^3 \text{ cm}^{-3}$, $U = 10^{-3}$, $\alpha = -1.5$, and (2) a starburst component, $n_H = 10^2 \text{ cm}^{-3}$, $U = 10^{-3}$, $T_* = 38\,000\text{K}$.

A grid of models was built varying the χ parameter, $\chi = 1, 5, 10$. As it can be seen in Fig. 18, we expect to have in the VO diagrams ratios intermediate between the HII and AGN case. This would be in agreement with the fact that in the sample of Storchi-Bergmann et alii those Seyferts which are classified as 'Seyfert+starburst', namely Seyfert galaxies with a strong circumnuclear star formation activity, are characterized by lower [OIII] $\lambda 5007/H\beta$ ratios (< 5) than 'pure' Seyferts. Given the above parameters, the best fit of the average VO line ratios for these objects is achieved with χ between 5 and 10. The same trend (line ratios intermediate between values obtained in the case of photoionization by stars and by a power-law) should be observed for other ratios such as e.g. MgII $\lambda 2798$ /CII] $\lambda 2326$, [OI] $\lambda 63$ /[NIII] $\lambda 57$. A comparison between model and observed line ratios is not possible in the UV and IR, since in these spectral ranges no line ratios are available for the 'Seyfert+Starburst' galaxies. However, HST is providing evidence about the existence of starburst regions in the inner ($\leq 500 \text{ pc}$) regions of Seyfert galaxies (Heckman et al. 1997): it is likely that data from the Space Telescope Imaging Spectrograph (STIS) will provide new data to be compared with models.

5. Conclusions

In this paper we gave a review of different line ratios which may be used in the diagnostics of Active Galactic Nuclei and starburst galaxies. We presented a series of isoratio plots which may be used in a first-order analysis to derive parameters such as the ionization parameter and the hydrogen density.

We then showed how the predictions from single-cloud models may be affected by more realistic physical assumptions, namely: (a) in the case of narrow-line spectra, the presence of an ensemble of clouds with different densities and (b) in the case of spectra taken through large apertures or high-redshift galaxies, the presence of circumnuclear HII regions ('hybrid' models).

We conclude that line ratios from single-component models may be used for a first-order classification of the ionization source in emission-line galaxies. However, more detailed models taking into account the environment of the emission-line regions should be considered when trying to determine physical parameters.

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Fig. 5: Line ratios in the ultraviolet range, stellar continuum models (Mihalas continuum, $T_* = 38\,000$ K). X axis: $\log n_H$, Y axis: $\log U$.

Fig. 6: Line ratios in the optical range, stellar continuum models (Mihalas continuum, $T_* = 38\,000\text{ K}$)

Fig. 7: Line ratios in the infrared range, stellar continuum models (Mihalas continuum, $T_* = 38\,000\text{ K}$)

Fig. 8: Line ratios in the ultraviolet range, power-law models ($\alpha = -2.0$)

Fig. 9: Line ratios in the optical range, power-law models ($\alpha = -2.0$)

Fig. 10: Line ratios in the infrared range, power-law models ($\alpha = -2.0$)

Fig. 11: Line ratios in the ultraviolet range, power-law models ($\alpha = -1.5$)

Fig. 12: Line ratios in the optical range, power-law models ($\alpha = -1.5$)

Fig. 13: Line ratios in the infrared range, power-law models ($\alpha = -1.5$)

Fig. 14: Line ratios in the ultraviolet range, power-law models ($\alpha = -1.0$)

Fig. 15: Line ratios in the optical range, power-law models ($\alpha = -1.0$)

Fig. 16: Line ratios in the infrared range, power-law models ($\alpha = -1.0$)

Fig. 17: Multi-density models: line ratios have been computed in high-density, $n_H = 10^5 \text{ cm}^{-3}$ (H), low-density $n_H = 10^3 \text{ cm}^{-3}$ (L) and composite (C) models. See text for the parameters of the models.

Fig. 18: Hybrid models: a thermal component (HII) is added with increasing weights (χ) to a non-thermal component (PL). The parameters of the models are given in the text. Squares show the average line ratios given by Storch-Bergmann et al. (1995) for Seyfert, Seyfert-Starburst and Starburst galaxies (decreasing values of $[OIII]/H\beta$).