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Lines of high excitation in NGC 4151: new measurements of [Fe X] and [Fe XIV]*

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Summary. We provide in this paper new measurements from high resolution data of the [Fe X] 6374.5 Å and [Fe XIV] 5303 Å emission lines in NGC 4151. Line blends have been analyzed properly through a quantitative separation technique: compared to previous results the accuracy is substantially improved.

The [O I] 6300.3 Å and 6363.8 Å line profiles match that of the [O III] 5006.8 Å line. Taking into account this property, we find that the [Fe X] 6374.5 Å line emission can be represented by a single component corresponding to the [O I], [O III] core emission, as long as kinematical parameters are concerned. In other words, the prominent [Fe X] line emission in NGC 4151 occurs at the emission systemic velocity – is not blue-shifted – with a value FWHM ~ 200 km s^{-1}. In the framework of AGNs photoionized models, this observation implies that the ionizing radiation may travel out to large distances and reach the NLR without being much attenuated. This result points towards a small covering factor in the NLR. Considering the set of previous [Fe X] line intensity estimates, together with their large uncertainties, we find no convincing evidence for time variability of this feature over the past 15 years.

We definitely detect the [Fe XIV] 5303 Å and [Ca V] 5309.2 Å emission lines in NGC 4151. The [Fe XIV] emission is marginally found to decrease when both the continuum and the broad Balmer components drop in this object.

Comparisons of the [Fe X]/[Fe XI] and [Fe XIV]/[Fe X] line ratios with theoretical predictions do not allow readily to discriminate between collisional and photoionized models.

Key words: high excitation lines – active galactic nuclei – NGC 4151

1. Introduction

Reliable measurements of high excitation lines in active galactic nuclei (AGN) might prove extremely useful to build more realistic models of these objects. Since high ionic species like Fe^{13+} and Fe^{9+} can result from either collisions or photoionizations, we are prompted to investigate the physical conditions in the region where the bulk of the [Fe X] 6374.5 Å and [Fe XIV] 5303 Å emission lines originate. In most recent AGNs models one considers that a hot tenuous confining medium is in pressure or thermal balance with partially ionized dense clouds in the broad and narrow line regions (e.g. Blumenthal and Mathews, 1979; Krolik et al., 1981). Then, do the high excitation iron lines arise from this hot corona-like structure or from the illuminated highly ionized part of the dense clouds? In the latter case, the intensity ratio of these two lines would provide valuable information on the input radiation field at energies from 0.2 to 0.4 keV, not obtainable from classical nebular lines.

On the theoretical side, the first step is to look whether the high excitation line intensities will allow one to discriminate between the two possible ionization mechanisms. A positive answer was given some years ago (Osterbrock, 1969; Nussbaumer and Osterbrock, 1970). However, progress in atomic physics for iron ions as well as in AGNs models makes it worthwhile to reexamine this question. On the observational side, the [Fe X] and [Fe XIV] lines are difficult to measure accurately because of their weakness and blend with nearby features. The only way out is to increase drastically the signal to noise ratio, provided the lines are close from being resolved.

As long ago as 1960, both [Fe X] and [Fe XIV] lines had been detected in NGC 4151 by O.C. Wilson (Oke and Sargent, 1968). The presence of [Fe X] has been confirmed since by most observers, although its intensity is still poorly known (Souffrin, 1968; Weedman, 1971; Osterbrock and Koski, 1976; Schmidt and Miller, 1980; Penston et al., 1984). The reality of the [Fe XIV] line emission, in contrast, has been disputed continuously (Weedman, 1971), some authors attributing the emission in that region rather to [Ca V] 5309.2 Å alone.

We observed the iron lines in the course of a long-term program, monitoring emission lines in NGC 4151 over the past 10 years. In the present work, we address the following questions: (i) Is there definitely an [Fe XIV] line emission in NGC 4151, as it is the case in other AGNs, III Zw77 (Osterbrock, 1981), Tol 0109-383 (Fosbury and Sansom, 1983) or NGC 3783 (Ward and Morris, 1984; Evans and Dopita, 1984)? (ii) What are the kinematical parameters of the [Fe X] and [Fe XIV] line emitting regions? (iii) What does the comparison between the observed and the theoretical line intensity ratios, I([Fe X])/I([Fe XI]) and I([Fe XIV])/I([Fe X]), imply regarding the ionization mechanism and the structure of the narrow line region (NLR) in NGC 4151?

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* All the observational material was collected at the Haute Provence Observatory (CNRS)

Table 1. Journal of observations

Spectrum	Date	λλ (Å)	Resolution		Slit	
			FWHM (Å)	Sampling (Å)	μm	arcsec
G 1800	1981 Apr 2	4510; 5580	2	0.3	250	1.2
G 1816	1981 Apr 6	5700; 6800	3	0.3	450	2.1
G 1819	1981 Apr 6	4850; 5860	2	0.3	450	2.1
G 2320	1983 Apr 16	5230; 5480	0.4	0.07	450	2.1
G 2325	1983 Apr 16	4760; 5780	1.8	0.3	450	2.1
G 2585	1984 Feb 4	5230; 5480	0.4	0.07	450	2.1
G 2609	1984 Mar 6	5700; 6800	1.6	0.3	450	2.1

2. The observational data set

The observations were performed with an electronographic device attached to the echelle spectrograph at the coudé focus of the 1.5 m telescope at Haute Provence Observatory (Baranne and Duchesne, 1976). Over the wavelength interval 4800–6800 Å, the use of various gratings provided resolutions from 0.4 Å to 3 Å (mean full width at half maximum of the comparison arc lines). Relevant data are presented in Table 1.

After being digitized, the data were reduced in a classical way. The spectra were all scaled to the same [Fe VII] 5721.1 Å line flux. No correction was applied for internal reddening which is small indeed and does not affect much this wavelength range.

Due to close blends and complex line profiles, careful line decompositions are required for improving the [Fe X] and [Fe XIV] line intensity measurements. This was achieved by using a least square fitting routine described previously (Pelat and Alloin, 1980).

3. The [Fe X] line emission

We present in Fig. 1 the wavelength region around [Fe X] 6374.5 Å, this line being blended with [O I] 6363.8 Å. Fortunately the [O I] 6363.8 Å and [O I] 6300.3 Å line intensities are within a theoretical ratio 1:3. Since the [O I] 6300.3 Å line is more intense and hence observed with a better signal to noise ratio, we study its profile first.

3.1. *The [O I] line profile analysis*

In spite of the contamination by the [S III] 6312.1 Å line on its red side, broad wings are clearly visible in the [O I] 6300.3 Å line, in particular to the blue. Because of the large critical density of this line, this result is consistent with the correlations, line width: critical density, and, blue-shift: critical density, already found for other objects like NGC 3783 (Pelat et al., 1981), NGC 7213 (Filippenko and Halpern, 1984), NGC 2110, I Zw92 and UM 16 (de Robertis and Osterbrock, 1985). Most probably in NGC 4151, this broad feature arises from the inner parts of the NLR where the filaments have a density of order $10^6\,\mathrm{cm}^{-3}$ and exhibit a

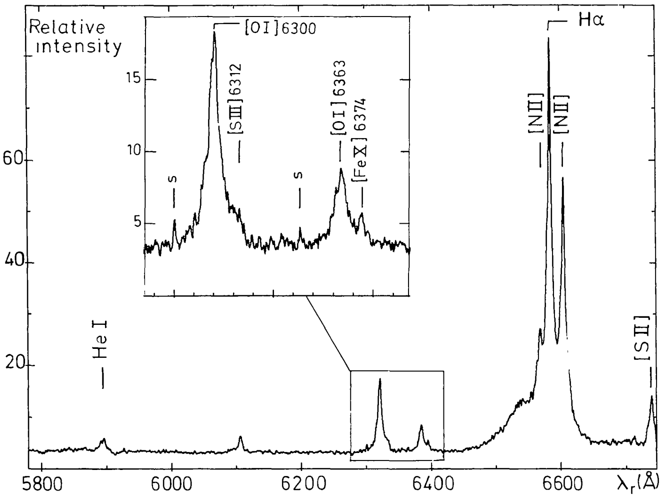

Fig. 1. The [Fe X], [O I] spectral region. The [O I] night sky lines (s) indicate the data resolution

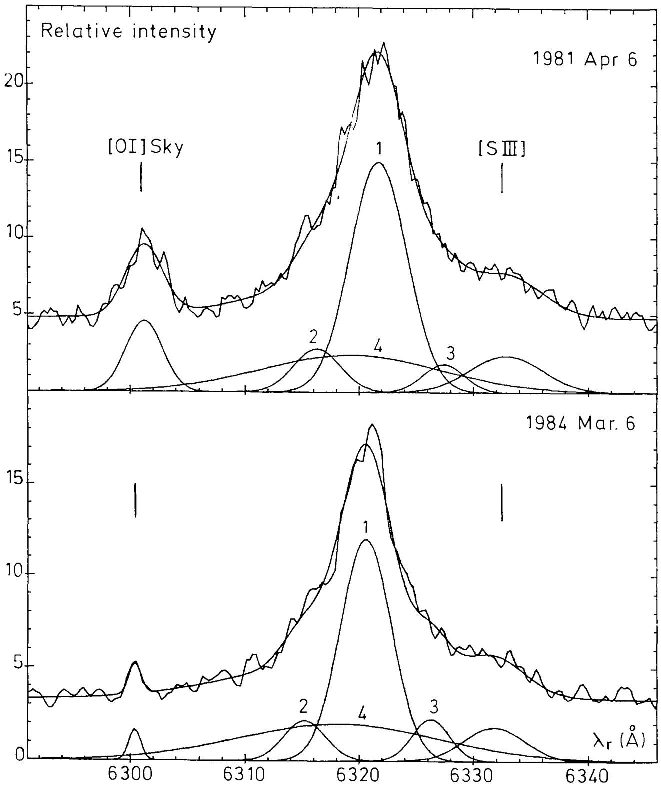

Fig. 2. Analysis into gaussian components of the [O I] 6300.3, [S III] 6312.1 Å blend. Components labelled 1, 2, 3 and 4 represent the [O I] 6300.3 line profile

Table 2. The [O I], [S III], [Fe X] line analysis

Comp. No.		1	2	3	4	Single comp.
FWHM	[O I] 6300[a]	265 ± 15	216 ± 12	190 ± 10	930 ± 50	
	[O I] 6364[a]	265 ± 15	216 ± 12	190 ± 10	940 ± 60	
	[S III] 6312[a]					320 ± 30
	[Fe X] 6374[a]					205 ± 25
	[O III] 5007	240	207	177	1805[b]	
$V_{em}/_{\odot}$	[O I] 6300[a]	968 ± 1	710 ± 1	1238 ± 1	850 ± 1	
	[O I] 6364[a]	975 ± 8	719 ± 8	1246 ± 8	858 ± 8	
	[S III] 6312[a]					933 ± 2
	[Fe X] 6374[a]					960 ± 17
	[O III] 5007	968	712	1239	851	
I_r^c	[O I] 6300[a]	54 ± 3	8.5 ± 0.5	6 ± 1	31.5 ± 2.5	
	[O I] 6364[a]	19 ± 0.5	2.8 ± 0.1	2.1 ± 0.4	11 ± 1.2	
	[S III] 6312[a]					10 ± 1
	[Fe X] 6374[a]					5.9 ± 0.7
I_r^d	[O III] 5007	36	12	5	47	

[a] We provide the mean value and dispersion obtained from fits at the two epochs 81 Apr 6 and 84 Mar 6

[b] The larger intensity in the [O III] 5007 Å line allows detection of the wings further out in the velocity space

[c] I([O I]) 6300 Å = 100

[d] I([O III]) 5007 Å = 100

general radial velocity $-150\,\mathrm{km\,s^{-1}}$ (considering a systemic velocity $995\,\mathrm{km\,s^{-1}}$ for NGC 4151).

The [O I] line core closely resembles that of the [O III] 5006.8 Å line (Pelat and Alloin, 1982) and cannot be fitted by a single gaussian component. In order to reduce the number of free parameters in the [O I], [S III] blend analysis, we have therefore taken the positions and widths of the [O I] core components (No. 1, 2 and 3) as well as the relative position of the broad component (No. 4), according to the corresponding features from the [O III] line profile study. The [O I], [S III] analysis at two different epochs are displayed in Fig. 2 and the mean associated parameters are given in Table 2.

3.2. *The [Fe X] line*

Resting on the previous [O I] line profile study and scaling it down by a factor 2.9, we have analyzed the [O I] 6363.8 Å, [Fe X] 6374.5 Å blend. The [Fe X] line can be matched by a single component (Table 2) with kinematical parameters (FWHM, V_{em}) close to the ones of the main component No. 1 in the [O I] core. In particular, *a broad blue-shifted [Fe X] component is not required* in this fitting experiment. Certainly, such a feature, if it exists, could not be easily disentangled from the red-shifted component No. 3 in the [O I] 6363.8 Å profile (Fig. 3). We estimate that, *at the present stage* and *because of the complex [O I] line profile*, it is not possible to decide on the presence of this [Fe X] broad component in NGC 4151, contrarily to other cases (Pelat et al., 1981; Penston et al., 1984).

3.3. *Discussion*

If one makes the assumption that the line profile is essentially ruled by macroscopic velocity fields, the kinematical parameters we observe for the [Fe X] line demonstrate that highly ionized species are still present in the outer parts of the NLR. In the framework of photoionized models this implies that a substantial fraction of the 0.2 keV radiation travels out to distances as large as 100 pc and this result would then argue for a small covering

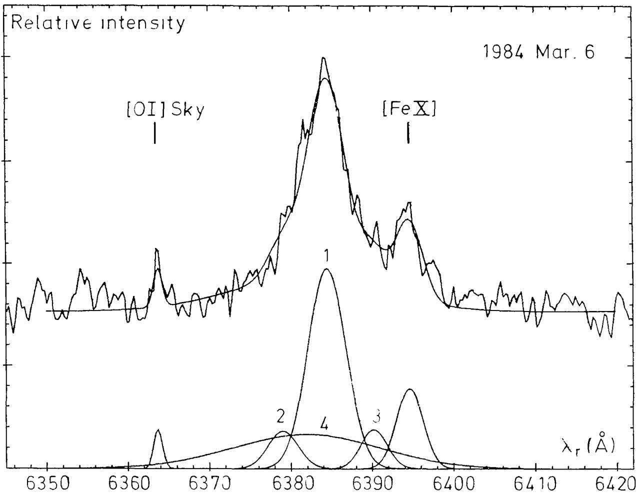

Fig. 3. Analysis into gaussian components of the [O I] 6363.8 Å, [Fe X] 6374.5 Å blend

Table 3. Comparison with previous observed intensities[a,b]

λ_0		Present work 1981–84	Osterbrock, Koski 1976	Boksenberg et al., 1975	Oke, Sargent 1968	Souffrin 1968
[Fe XIV]	5302.9	6 ± 2			9	
	5303.6					
[Ca V]	5309.2	10 ± 3	11	11.5		4
[Fe VII]	5721.1	23 ± 3	24	17	36	15
[Fe II]	5750.9	15 ± 2	7.5	10.5		
[N II]	5754.8					
[Fe VII] [Ca V]	6086.9	32 ± 4	28	34	62	64
[O I]	6300.3	146 ± 10	139	161	161	161
[S III]	6312.1	15 ± 3	22			
[O I]	6363.8	47	44	57	36	46
[Fe X]	6374.5	8 ± 2	15		18	34

[a] Intensities relative to [O I] 6300.3 Å core (components = 1, 2, 3)

[b] I([Fe XI]) = 18 (Grandi, 1978) in the same unit

factor in the NLR. In fact, at any distance from the centre, the kinematical parameters governing the profile are likely to be the same, whether the emission arises in dense clouds or in the hot diluted medium pressure balancing them. Consequently, would the [Fe X] line emission rather originate in a corona-like component at $T \sim 10^6$ K, we would be detecting this hot medium in the outer part of the NLR. Clouds in this region having a density around $10^4\,\mathrm{cm}^{-3}$ and a temperature $T_e \sim 10^4$ K, the density of the confining medium there, should be roughly $10^2\,\mathrm{cm}^{-3}$.

From studies of the broad [Fe X] component in other AGNs (Pelat et al., 1981; Penston et al., 1984) a characteristic size of 1 pc or less was inferred for the Fe^{9+} emitting region and hence, [Fe X] line variations expected on a time scale of a few years. Would this figure hold true for NGC 4151, although we cannot measure the broad [Fe X] component alone, a change in intensity of the blend [O I] 6363.8 Å + [Fe X] might reveal variability in the Fe^{9+} zone. We estimate that, without a proper separation, earlier intensity measurements of the faint blended [Fe X] line could certainly not be achieved with a precision better than 50%, this being still an optimistic figure. Penston et al. (1984) provide a compilation of 7 published [Fe X]/([O I] 6300.3 Å + [S III]) line ratios, their mean value and dispersion being: 0.075 ± 0.04. Our new measure is 0.05 ± 0.02, consistent with previous estimates and, *at face value, variability of the [Fe X] line cannot be derived from these data.* Considering the blend [O I] 6363.8 Å + [Fe X], again the intensity values are rather constant (Table 3) apart from an old measurement derived from photographic spectra. We conclude that a more precise data base and a refined analysis are required before [Fe X] line variability can be claimed to occur in NGC 4151. In addition, while we observed a noticeable change in the broad Balmer line component (−25% at Hα) over the period 81 April 6 to 84 March 6, the [O I] 6363.8 Å + [Fe X] intensity blend did not vary significantly.

4. The [Fe XIV] emission feature: a positive detection

We present in Fig. 4, two of the NGC 4151 spectra in the wavelength region 5100–5500 Å and compare them to that of III Zw77 (Osterbrock, 1981). Could the observed emission around 5303, 5309 Å be due to [Ca V] alone in NGC 4151? Then, this line would have a core with FWMH ~ 720 km s^{-1}, significantly larger than that observed in the [O III], [O I] and [Fe X] lines, around 300 km s^{-1}. We find it more likely that this emission feature represents a blend of the [Fe XIV] 5303 Å and [Ca V] 5309.2 Å lines. In order to improve the signal to noise ratio and therefore the separation of the two lines, we have added four spectra in that spectral range. A satisfactory fit to the blend is provided by two gaussian components at the emission systemic velocity (995 km s^{-1}) having FWHM of 350 and 460 km s^{-1}, for [Fe XIV] and

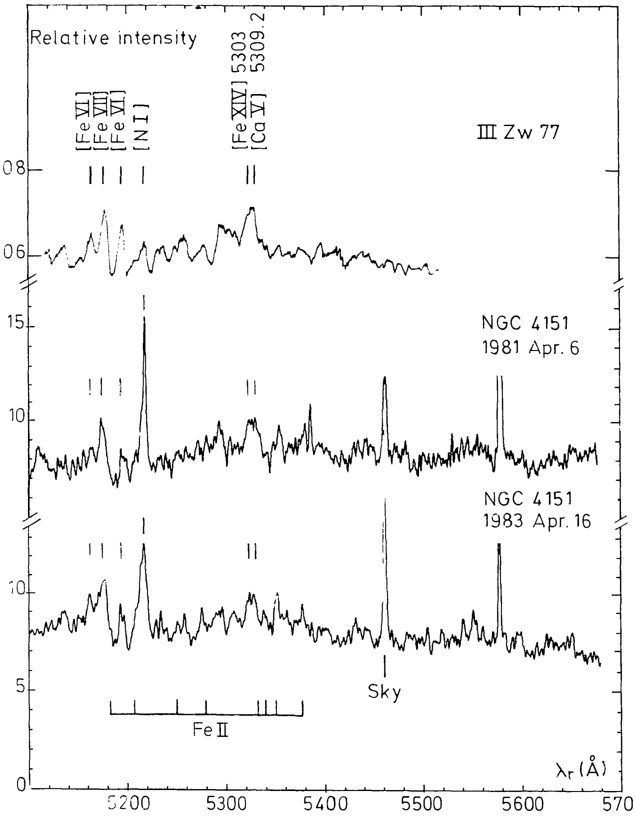

Fig. 4. The [Ca V], [Fe XIV] spectral region: a comparison between NGC 4151 at two different epochs and III Zw77 (Osterbrock, 1981)

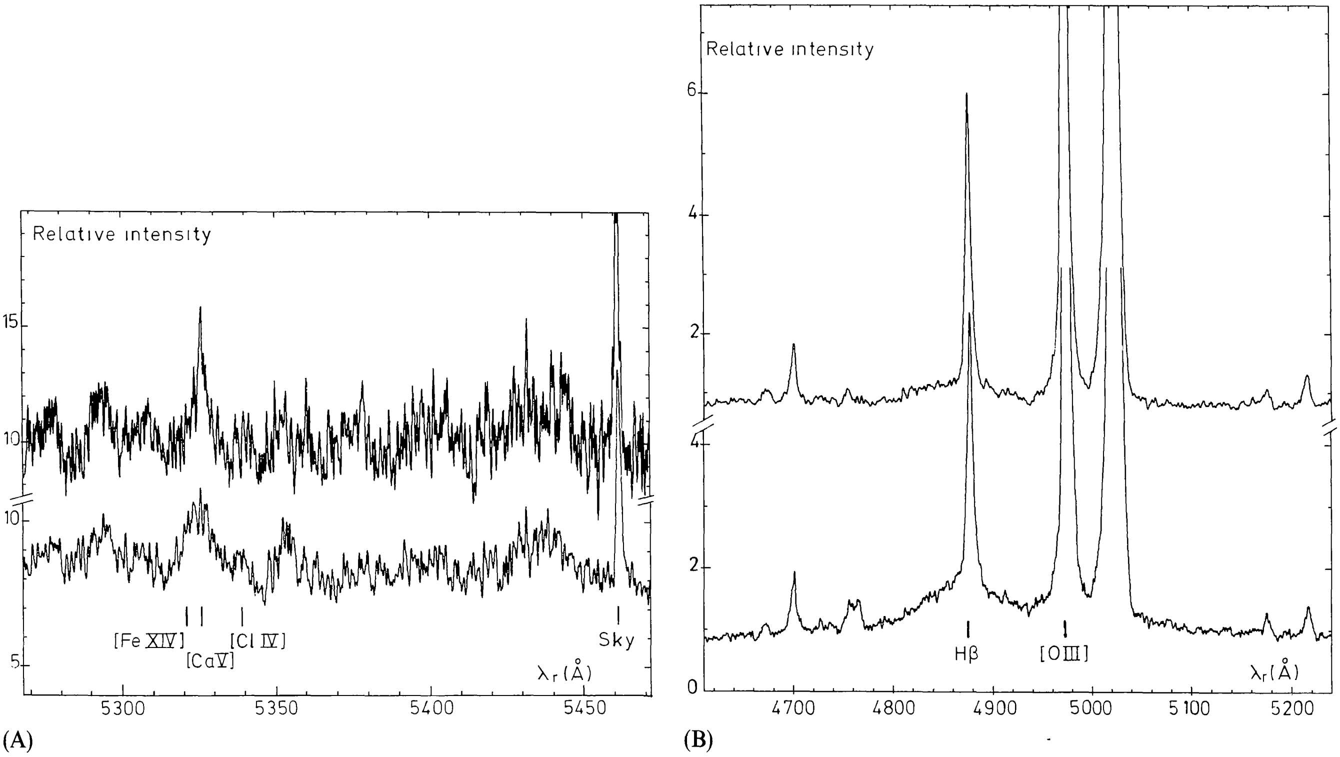

Fig. 5. **a** The [Fe xiv], [Ca v] spectral region at two different epochs: upper on 1984 Feb. 4, resolution 7 Å; lower on 1983 Apr. 16, resolution 11 Å. **b** The Hβ, [O iii] spectral region at approximately the same epochs: upper on 1984 Feb. 5; lower on 1983 Apr. 13

[Ca v], respectively. The resulting intensities are given in Table 3. In addition to the previous analysis, a quantitative separation of the blend performed on the high resolution data (G 2320) has produced similar results.

We conclude on a positive detection of the [Fe xiv] 5303 Å line in NGC 4151. From the data displayed in Fig. 5a, there is marginal evidence for profile changes of the blend [Fe xiv], [Ca v] suggesting that the [Fe xiv] line intensity might vary on time scales smaller than 10 months. Interestingly, a substantial decrease of both the broad Balmer component and the continuum was detected over the same period (Fig. 5b). The [Fe xiv] line is so faint however, that further observations are required before we understand its temporal behaviour.

5. Concluding remarks

From these new [Fe x] and [Fe xiv] line measurements together with the [Fe xi] 7892 Å line intensity (Grandi, 1978) we derive

Table 4. Comparison between predicted line ratios and observed ones in NGC 4151

	Models				Observations	
	Collisional[a] $T_e = 10^6\,\mathrm{K} \rightarrow 1.5\,10^6\,\mathrm{K}$	Photoionization [b]	 [c]	 [d]	NGC 4151	III Zw77
$\frac{I([\mathrm{Fe\,x}])}{I([\mathrm{Fe\,xi}])}$	2.2 → 0.46	0.9	11	1.1	0.35 ± 0.1	2.
$\frac{I([\mathrm{Fe\,xiv}])}{I([\mathrm{Fe\,x}])}$	0.002 → 1.1	0.11		0.44	0.8 ± 0.4	0.3

[a] Mason (1975)

[b] Osterbrock (1969). This calculation assumed a cloud density $N_e = 10^4\,\mathrm{cm}^{-3}$, a filling factor $\varepsilon = 10^2$ and $\alpha = 1.24$

[c] Grandi (1978). The same physical parameters were considered. Different atomic constants and abundance values were used

[d] Stasinska (1986). The following set of physical conditions was considered: $N_e = 10^4\,\mathrm{cm}^{-3}$, $\alpha = 1.5$ and $U = 1$. The ionizing parameter U is defined as: $U = Q_H/4\pi r^2 N_e c$, where Q_H is the total number of photons with energies greater than 13.6 eV, emitted by the ionizing source per unit time, r is the distance of the cloud to the source and c is the speed of light. Such a large value of U is expected in regions less than 1 pc from the central engine

the following ratios:

$$I([\mathrm{Fe\,XIV}])/I([\mathrm{Fe\,X}]) = 0.8 \pm 0.4$$

$$I([\mathrm{Fe\,X}])/I([\mathrm{Fe\,XI}]) = 0.35 \pm 0.1.$$

The corresponding figures from the spectrum of III Zw77 (Osterbrock, 1981) are respectively 0.3 and 2.0 as a result of a larger [Fe x] line intensity with respect to both [Fe xi] and [Fe xiv]. For NGC 3783, only the [Fe x] over [Fe xi] line ratio is available, with a mean value of 1.6 (Ward and Morris, 1984).

In Table 4 we compare these ratios to theoretical predictions assuming two different ionization mechanisms: (i) via collisions in a diluted medium at a temperature around 10^6 K (Mason, 1975), as required for cloud confinement in the NLR, and (ii) via photoionizations from a central source ($f_\nu \propto \nu^{-\alpha}$) illuminating a set of dense clouds in the NLR (Osterbrock, 1969; Grandi, 1978; Stasinska, 1986). One can see that the line ratios observed in NGC 4151, contrarily to the case of III Zw77, can hardly be explained in terms of photoionization. However we stress the fact that high excitation lines of iron, from [Fe xiv] down to [Fe v], which are now observed with some accuracy in NGC 4151, have not been given yet enough attention as regards models. On the other hand, in the framework of collisional ionization, these line ratios are extremely sensitive to gas temperature, a parameter rather badly known. Indeed, the [Fe x], [Fe xi] and [Fe xiv] line intensities alone do not allow a clear discrimination between the two ionization mechanisms considered. A whole set of emission lines from low to high excitations should rather be compared to predicted values from any particular model, in order to restrict the variation interval of the model parameters.

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