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NARROW-LINE SEYFERT 1 GALAXIES: THE [O III] λ5007/Hβ RATIO AND PHOTOIONIZATION MODELS FOR THE NLR

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RESUMEN

Estudiamos los perfiles ópticos y las condiciones físicas de la región de líneas estrechas (NLR) de galaxias Seyfert 1 con líneas estrechas (NLS1s). Los resultados muestran que el flujo asociado a la componente estrecha de Hβ puede ser un factor de hasta 10 veces mayor que el valor usualmente adoptado en la literatura. Como consecuencia, la razón [O III] λ5007/Hβ oscila entre 1 hasta 5, en lugar del valor de 10 comunmente adoptado. Probamos modelos de fotoionización que consideran una NLR compuesta de una combinación de nubes limitadas por materia y limitadas por radiación y mostramos que este escenario reproduce de forma satisfactoria las razones de líneas de emisión observadas. Proponemos que las propiedades peculiares de la NLR en las NLS1s pueden ser explicadas por un continuo inclinado de tipo ley de potencia en la region EUV–Rayos-X blandos, con un índice espectral $\alpha \sim -2.2$, consistente con las observaciones *ROSAT* realizadas en esta clase de objetos.

ABSTRACT

We study optical profiles and the physical conditions of the narrow line region (NLR) of narrow-line Seyfert 1 galaxies (NLS1s). Our results show that the flux carried out by the narrow component of Hβ can be up to 10 times higher than the value usually adopted in the literature. As a result, the [O III] λ5007/Hβ ratio emitted in the NLR varies from 1 to 5, instead of the universally adopted value of 10. We test photoionization models that consider a NLR composed of a combination of matter-bounded and ionization-bounded clouds and show that this scenario reproduces with very good agreement the observed emission lines ratios of NLS1s. We propose that the peculiar properties of the NLR of NLS1s can be explained by a steep continuum of power-law form in the EUV–soft X-ray region, with spectral index $\alpha \sim -2.2$, consistent with *ROSAT* observations of this class of objects.

Key Words: **GALAXIES: SEYFERTS — X-RAYS: GALAXIES**

1. INTRODUCTION

Narrow-Line Seyfert 1 galaxies (hereafter NLS1s) are a sub-class of Seyfert 1 galaxies that displays very peculiar and interesting properties. Among others, the permitted optical broad lines show full width at half-maximum (FWHM) values not exceeding 3000 km s^{-1}; the [O III] λ5007/Hβ ratio is usually low (< 3); the Fe II emission is strong; and the observed spectrum is rich in high ionization forbidden lines. In the X-ray region, NLS1s have generally much steeper continuum slopes and rapid variability (Boller, Brandt, & Fink 1996; Leighly 1999) and a soft excess emission appears considerably more frequently in NLS1s than in normal Seyfert 1s (hereafter Sy1s).

In this work we are interested in the study of the properties of the narrow line region (NLR) of NLS1s galaxies. Except for a few spectral studies (Osterbrock & Pogge 1985; Stephens 1989), no quantitative analysis

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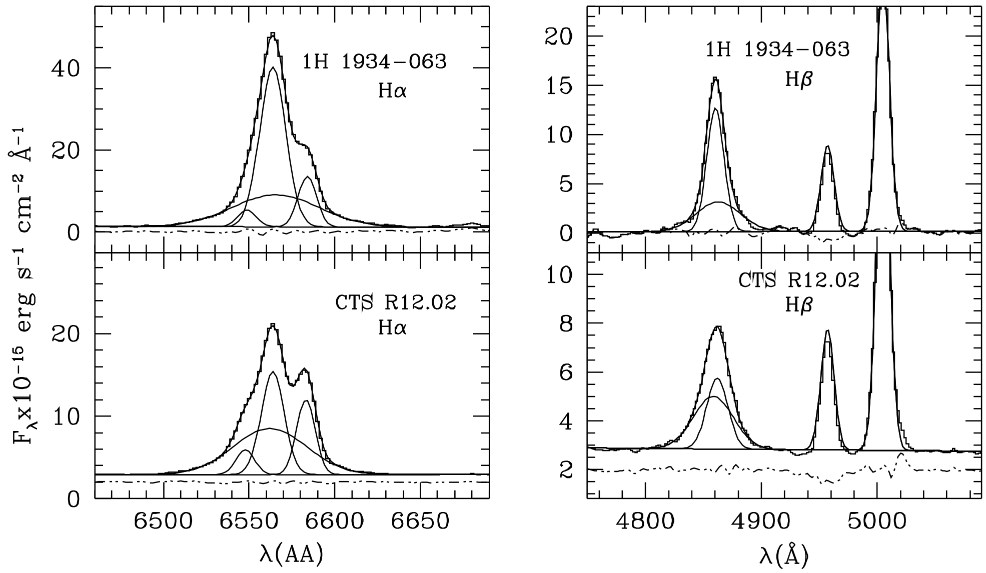

Fig. 1. Example of the Gaussian decomposition applied to Hα (left panels) Hβ (right panels) in the NLS1 galaxies 1H 1934-063 and CTS R12.02. Note the presence of the "broad" component fitted to the Balmer lines. The histogram is the data, the solid lines are the Gaussian components and the dashed line represent the residuals of the fit.

involving NLR emission line ratios have been done so far. This is in part due to the difficulty in separating the NLR contribution from the permitted lines because no inflections in the line profiles, as those normally observed in Sy1s, are seen in NLS1s. For this reason, it is necessary to perform a closer analysis of the NLR ratios and estimate the actual contribution of the narrow Hβ flux to the total Hβ emission line. The data available to this purpose consist of long-slit spectroscopic observations of a sample composed of seven NLS1 galaxies covering the spectral region 3700 – 9500 Å. Details of the observing setup and the reduction procedure have been described elsewhere (Rodríguez-Ardila, Pastoriza, & Donzelli 2000, hereafter Paper I). § 2 shows the decomposition into narrow and broad component applied to the permitted line profiles, in § 3 photoionization models for the NLR of NLS1s are presented and § 4 gives the main conclusions of this work.

2. ANALYSIS OF THE PERMITTED EMISSION LINE PROFILES

It is well known that the permitted line profiles of Sy1 galaxies are composed of the contribution emitted by the broad line region (BLR) and that from the NLR. In classical Sy1 galaxies, separating these two contributions is relatively easy given the strong inflection that naturally separates the narrow profile from the broad one. In NLS1s, this is a difficult task given that no transition between the two components is usually seen.

In order to characterize the emission line profiles of the NLS1s we have assumed that they can be represented by a single or a combination of Gaussian profiles. In all cases, a single narrow component to the permitted lines give a poor representation of the observed profile, being necessary the addition of a second broad component (FWHM ~ 2500 km s^{-1}) to get a satisfactory fit. Figure 1 shows the results of this decomposition for 1H 1934-063 and CTS R12.02. The left panels present the best solution found for the Hα region and the right panels the fit to the Hβ + [O III]λλ4959,5007 lines.

Columns 2 to 7 of Table 1 list the FWHM (in km s^{-1}) of the emission lines measured from the Gaussian fitting. The flux ratio of the narrow to the broad component of Hβ for each galaxy is listed in Column 8 and the [O III] λ5007 flux, relative to the narrow Hβ component, is in Column 9. Note the good similarity between the narrow FWHM of the permitted and forbidden lines within the same galaxy and between the FWHM of the "broad component" found in Hα and Hβ.

We interpret the broad component found in the Balmer lines of the NLS1 galaxies as emission from the

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TABLE 1

FWHM[a] (IN $\mathrm{km\ s^{-1}}$) AND FLUX LINE RATIOS OF NLS1S.

Galaxy	FWHM Hα Narrow	FWHM Hα Broad	FWHM Hβ Narrow	FWHM Hβ Broad	FWHM λ5007	FWHM λ6584	$F\left(\frac{H\beta_N}{H\beta_B}\right)^b$	$F\left(\frac{\lambda 5007}{H\beta_N}\right)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1H 1934-063	743	2703	926	2706	562	446	1.6	2.2
CTS H34.06	552	2401	972	2109	560	420	1.2	1.8
CTS J03.19	360	1766	560	1932	570	360	0.5	5.0
CTS J04.08	405	2152	560	2628	584	424	0.5	3.3
CTS J13.12	635	2212	762	3155	590	360	2.2	0.8
MRK 1239	637	2278	683	2968	565	360	1.1	2.7
CTS R12.02	625	2272	1200	2434	583	448	0.7	3.4

(a) The contribution to these FWHM from the instrumental profile ($\sim 360\ \mathrm{km\ s^{-1}}$ at Hα) has been removed.

(b) The N and B subscripts refer to the narrow and broad flux, respectively.

BRL, similar to that observed in normal Seyfert 1 galaxies but with a smaller FWHM, supporting the results of Rodríguez-Pascual, Mass-Hesse, & Santos-Lléo (1997) and Gonçalves, Véron, & Véron-Cetty (1999) who also report a broad component in the permitted lines of NLS1s. It is clear from the values of column 8 in Table 1 that the narrow permitted lines of NLS1s show a significantly larger contribution in flux relative to that from the BLR than classical Seyfert 1s do. On average, the fraction of NLR flux in the observed Hβ line equals to 50% of the total line flux. In contrast, the ratio $F(H\beta_n/H\beta_b)$ in normal Seyfert 1 galaxies is usually around 0.1 (Paper I). This result by itself does not represent a major departure from our current picture of NLS1s. However, a significant difference emerges when we consider line ratios between the narrow component of Hβ and [O III] λ5007, for instance.

In effect, since Osterbrock & Pogge (1985) and up to very recently (Leighly 1999), it has been assumed that the contribution in flux of the narrow component of Hβ to the NLR spectrum of a given object equals 10% of the flux of [O III] λ5007. This assumption is based on the fact that [O III] λ5007/Hβ is, on average, ∼ 10 in Seyfert 2 galaxies (Veilleux & Osterbrock 1987). Nonetheless, growing evidence of important differences between the NLR of Sy1 and Seyfert 2 galaxies have appeared in the literature (Schmitt & Kinney 1996; Schmitt 1998; Paper I). In addition, NLS1s are recognized as a subclass within the realm of Sy1s due to their peculiar properties, making very unlikely that the above assumption really holds in these objects. The values of the [O III] λ5007/Hβ(narrow) ratio found for our sample confirms our initial suspicion. These present not only a wide intrinsic dispersion but, more importantly, they are significantly lower (0.8 to 5) that those found in normal Sy1s.

3. PHOTOIONIZATION MODELS FOR THE NLR OF NLS1S GALAXIES

The results of the preceding section point to intrinsically low [O III] λ5007/Hβ ratios in NLS1s, with values more typical of some starburst or H II galaxies than of canonical Sy1 or 2s. In addition, Paper I presented observational evidence suggesting: *(i)* NLS1s have intrinsically weak low ionization forbidden lines; *(ii)* the [O III] zone is characterized by high temperatures ($T_{[OIII]} \sim 16000$ K); *(iii)* a wide range of densities ($10^3\ \mathrm{cm^{-3}}$ – $10^6\ \mathrm{cm^{-3}}$) must exist in the NLR of these objects.

A scenario which springs naturally from the above results invokes the presence of at least two types of clouds. A denser, *inner* set of high excitation matter-bounded (MB) clouds where most of the [O III] and higher excitation lines are formed and an *outer* (relative to the position of MB clouds) less dense set of ionization-bounded (IB) clouds, responsible for the production of low-ionization lines such as [O I], [N II] and [S II]. The starting hypothesis is that the relative proportion of these two types of clouds combined with a

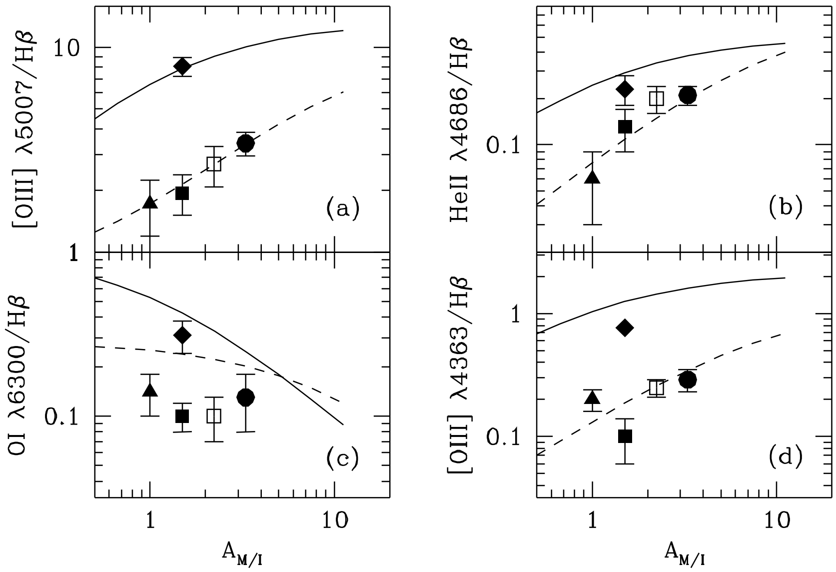

Fig. 2. Theoretical emission line ratios as function of the relative proportion of MB and IB clouds: $A_{M/I}$. The solid line corresponds to the predicted narrow line ratios using the SED labelled NGC 5548 while the long-dashed line represent the ratios using the SED labelled NLS1 (see text). The filled triangle, square and circle and the open square are the observed dereddened line ratios of the NLS1 galaxies CTS H34.06, 1H 1934-063, CTS R12.02 and MRK 1239, respectively. The diamond corresponds to the normal Seyfert 1 galaxy NGC 5548.

suitable choice of the input ionizing continuum (Binette, Wilson, & Storchi-Bergmann 1996) will reproduce the observed differences between the NLR of NLS1s and that of normal Seyfert 1 galaxies.

The above approach was tested in order to see if it can account for the anomalous line ratios observed in NLS1s. Of particular interest is the determination of the spectral energy distribution (SED) which best reproduces the observed [O III] $\lambda5007/\mathrm{H}\beta$ range of 1 – 5 as well as other strong lines while using similar physical parameters to those employed to model the NLR of normal Sy1 galaxies. For this reason, a function representative of the observed continuum in normal Seyfert 1 galaxies was assumed, namely that derived by Kraemer et al. (1998) for the archetypical Seyfert 1 galaxy NGC 5548. A second distribution, formed by the mean spectral indices in the EUV–X-ray region measured from a sample of NLS1 galaxies by Leighly (1999) was taken as representative of the NLS1s. These two functions can de described by broken power-laws of the type $F_\nu = K\nu^\alpha$ where:

$$\begin{array}{lllll} \mathrm{SED\ \ NGC\ 5548:} & \alpha = -1.4, & 13.6 \le h\nu \le 1300\mathrm{eV}; & \alpha = -0.4, & h\nu \ge 1300\mathrm{eV}\ , \\ \mathrm{SED\ \ NLS1:} & \alpha = -2.2, & 13.6 \le h\nu \le 2000\mathrm{eV}; & \alpha = -1.1, & h\nu \ge 2000\mathrm{eV}\ . \end{array}$$

For each of the above two SEDs, the $A_{M/I}$ parameter, which characterizes the relative proportion of MB and IB clouds, was varied from 0.04 to 11. Density estimates of the NLR of NLS1s based on density and temperature line ratios (cf. Paper I) show that MB clouds should have $n_e \sim 10^6$ cm^{-3} while for IB clouds $n_e \sim 10^3$ cm^{-3}. The ionization parameter U_{MB} at the illuminated face of the MB clouds was initially set to $10^{-1.5}$, following estimates of Rodríguez-Ardila, Pastoriza, & Maza (1998) and Kraemer et al. (1998) for normal Sy1 galaxies. The multipurpose code MAPPINGS Ic (Ferruit et al. 1997) was used to compute the photoionization models.

Figure 2 shows the predicted [O III] $\lambda5007$, He II $\lambda4686$, [O I] $\lambda6300$ and [O III] $\lambda4363$, relative to Hβ (narrow) as function of the relative proportion of MB and IB clouds, $A_{M/I}$. In order to compare the output with the observations, we have plotted the *dereddened* observed ratios for the NLS1 galaxies CTS H34.06, 1H 1934-063, CTS R12.02 and MRK 1239 as taken from Paper I. NGC 5548 was chosen as representative of the normal Seyfert 1 galaxies, with the corresponding dereddened ratios taken from Kraemer et al. (1998).

The results show that overall the MB-IB scenario is successful at reproducing the most important observed line ratios. Since the model parameters were rather similar for the two SEDs, the results provide a strong support to the idea that the NLR of NLS1s and Sy1s have similar physical properties in terms of density, chemical abundance, ionization parameter and distance to the central source. The most probable cause of the observed spectral differences can be related to a different value of the spectral index α in the EUV – soft-X ray region of their respective ionizing continuum.

4. DISCUSSION OF THE RESULTS

According to Section 2, the NLR of NLS1s contributes, on average, 50% of the total Hβ emission. This has important implications for the determination of the intrinsic ratios of the narrow lines of NLS1s. For instance, the [O III] λ5007/Hβ (narrow) ratio now falls within the interval 1–5 essentially because the narrow component of Hβ is ten times more intense than the previously assumed value.

The photoionization models clearly support these results. If we had assumed that in NLS1s the [O III] λ5007/Hβ (narrow) ratio took the canonical value of 10 of normal Seyferts, a spectral index $\alpha \sim -1.4$ would have been inferred. This goes against *ROSAT* observations of NLS1s, which show that their soft X-ray spectra is systematically steeper ($\alpha \sim -2$ or smaller) than those from normal Sy1 galaxies with broad optical lines. Some kind of continuum alteration or reprocessing would have to be invoked in order that the energy distribution seen by the NLR be different from that which we observe. This is unnecessary, however, as shown above since by simply adopting a SED typical of NLS1s with a similar set of initial conditions as employed to model NGC 5548, we easily obtain [O III] λ5007/Hβ ratios smaller than 7, which are fully consistent with the results of § 2.

We conclude that the main NLR spectral differences between NLS1s and normal Seyfert 1s can be explained in terms of differences between the steepness of the continuum energy distribution which illuminates the emission region. Other parameters such as density, temperature, distance of the emitting clouds from the central source and ionization parameters appear to be comparable in both type of objects.

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