THE O I LINE EMISSION IN ACTIVE GALACTIC NUCLEI REVISITED

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ABSTRACT

UV, visible, and near-infrared spectroscopy is used to study the transitions of neutral oxygen leading to the emission of broad O I \(\lambda\lambda 8446, 11287\), and \(\lambda\lambda 304\) in active galactic nuclei. From the strength of the former two lines, contrary to the general belief, we found that in six of seven galaxies, Ly\(\beta\) fluorescence is not the only mechanism responsible for the formation of these three lines. Because O I \(\lambda 13165\) is almost reduced to noise level, continuum fluorescence is ruled out as an additional excitation mechanism, but the presence of O I \(\lambda 7774\) in one of the objects suggests that collisional ionization may have an important role in the formation of O I \(\lambda 8446\). The usefulness of the O I lines as a reliable reddening indicator for the broad-line region is discussed. The values of \(E(B-V)\) derived from the \(\lambda\lambda 1304/\lambda 8446\) ratio agree with those obtained using other reddening indicators. The observations point toward a break in the one-to-one photon relation between \(\lambda 8446\) and \(\lambda 1304\), attributable to several destruction mechanisms that may affect the latter line.

Subject headings: galaxies: nuclei — galaxies: Seyfert — radiation mechanisms: thermal

1. INTRODUCTION

Permitted transitions of O I in the spectra of gaseous nebu-
lae are very important tracers of atomic processes other
than recombination, as well as indicators of the physical
conditions of the emitting gas. For many years, O I \(\lambda 8446\),
usually the strongest O I line in the optical region, has been
broadly studied in a large number of objects such as the
Orion Nebula (Morgan 1971; Grandi 1975), planetary nebu-
lae (Grandi 1976), and the pre–main-sequence Herbig
AeBe star LK\(\alpha\) 101 (Rudy et al. 1991). In active galactic
nuclei (AGNs), this feature is very common. Grandi (1980)
presented observational data showing that its strength
could reach several percent of H\(\alpha\). He associated the O I
emission with a phenomenon restricted to the broad-line
region (BLR). Later, Morris & Ward (1989) showed the
difficulty of a Ly\(\beta\) photon. In addition, the photon flux ratio between \(\lambda 11287\) and \(\lambda 8446\) should be unity since every \(\lambda 11287\) photon leads
to the emission of exactly one \(\lambda 8446\) photon. Smaller values
of this ratio should indicate the presence of recombination,
continuum fluorescence, or other processes that enhance
\(\lambda 8446\) but not \(\lambda 11287\).

Determining the mechanisms leading to the O I emission
in AGNs is important for various reasons. If Ly\(\beta\) fluores-
cence is dominant, photons of this line are converted to
those of neutral oxygen, affecting the population of the
excited levels of hydrogen. This process would act as a cool-
ing agent for the regions where the hydrogen lines are very
optically thick. Therefore, it is a process that must be taken
into account when using photoionization modeling to
describe the state of the BLR. Also, the O I lines can be used
as a reliable reddening indicator for the BLR if the contribu-
tions of the different processes to the line flux are known in
advance.

To the best of our knowledge, the only simultaneous
detection of O I \(\lambda 8446\) and \(\lambda 11287\) in an AGN was reported
by Rudy et al. (2000) for I Zw 1. Previously, Rudy, Rossano,
& Puetter (1989) reported the detection of O I \(\lambda 11287\) for
that same object. Combining previous measurements of \(\lambda 8446\) taken from Persson & McGregor (1985), Rudy et al.
(1989) found that the ratio of photon fluxes between these
two lines was equal to unity, providing a direct confirmation
that the broad permitted O I lines observed in an AGN arise
through Ly\(\beta\) fluorescence. Interestingly, in the spectrum of
I Zw 1 recently published by Rudy et al. (2000), with a
higher resolution and spectral coverage, the photon flux
ratio between \(\lambda 11287\) and \(\lambda 8446\) that we derive from their
data is 0.76. If this ratio is corrected for the \(E(B-V)\) of 0.16

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adopted by these authors, it does not appreciably change, but decreases to 0.74. Thus, contrary to what has been claimed, Ly$\beta$ fluorescence seems not to be the only mechanism contributing to the production of $\lambda$8446.

We have started a program to simultaneously measure O I $\lambda$8446, $\lambda$11287, and $\lambda$3165 in a sample of AGNs. Our goal is to establish if there is an excess of $\lambda$8446 emission, as in I Zw 1, indicating that Ly$\beta$ fluorescence is not the only excitation process that may give rise to the broad permitted O I lines. For this purpose, near-infrared spectroscopy at moderate resolution ($R \sim 320$ km s$^{-1}$) covering the spectral range 0.8–2.4 $\mu$m was obtained. By combining these observations with quasi-simultaneous visible spectroscopy and archival Hubble Space Telescope (HST)/International Ultraviolet Explorer (IUE) spectra, we expect to obtain additional information about the radiation processes that govern the O I emission and to test the usefulness of the O I lines as a reddening indicator for the BLR. The observations are presented in § 2, and a review of the principal mechanisms for the production of the O I lines is given in § 3. A discussion of the results appears in § 4. Our conclusions are in § 5.

2. OBSERVATIONS

2.1. The Sample

The sample of galaxies used in this work is composed of six narrow-line Seyfert 1 galaxies (NLS1s) and one classical Seyfert 1 galaxy. All seven objects show bright O I $\lambda$8446, so it is expected that if Ly$\beta$ is the dominant excitation mechanism for the O I emission, O I $\lambda$11287 should also be present at a similar intensity. In addition, data in the UV and optical region are available for the selected sample to help to distinguish other processes that can also contribute to the formation of broad O I lines. The reason for the predominance of NLS1s in the sample is that permitted lines in these objects are relatively narrow, minimizing the effects of blending with adjacent features. For example, the red wing of $\lambda$8446 is very close in wavelength to the two Ca II lines located at $\lambda$8498 and $\lambda$8542. Table 1 lists the objects selected for this study as well as their relevant characteristics. Except for I Zw 1, for which the flux measurements were drawn from the literature, our own observations or archival data are used for the remaining objects, as described in the following sections.

2.2. Near-Infrared Spectroscopy

Near-infrared spectra providing continuous coverage between 0.8 and 2.4 $\mu$m were obtained at the NASA 3 m Infrared Telescope Facility (IRTF) on 2000 October 11 (UT) with the SpeX facility spectrometer (Rayner et al. 1998). The detector consists of a 1024 × 1024 ALADDIN 3 InSb array with a spatial scale of 0.012 pixel$^{-1}$. Simultaneous wavelength coverage is carried out by means of prism cross-dispersers. A 0′8 × 15′′ slit was used during the observations, giving a spectral resolution of 320 km s$^{-1}$. The seeing was near 1′′ during the exposures. Table 2 summarizes the log of these observations.

Details of the spectral extraction and wavelength calibration procedures are given in Rodriguez-Ardila et al. (2002). The spectral resolution was sufficiently high so that in all cases O I $\lambda$8446 could be cleanly isolated from the Ca II lines. O I $\lambda$11287 is located in a region free of nearby emission features, so its line profile is well defined. Figure 1 shows the observed O I lines plotted on a laboratory wavelength scale.

2.3. Optical Spectroscopy

Optical spectra covering simultaneously H$\alpha$ and H$\beta$ were available for all the target objects except NGC 863. Long-slit spectroscopic observations of 1H 1934–063, Mrk 335, Mrk 1044, and S180 were obtained with the Complejo Astronómico El Leoncito 2.15 m Telescope using a Tek

### Table 2

| Galaxy       | Instrument | Grating (lines mm$^{-1}$) | Coverage (Å) | Exposure Time (s) | Date of Observation |
|--------------|------------|----------------------------|--------------|-------------------|---------------------|
| 1H 1934–063  | IRTF       | ...                        | 8000–24000   | 2700              | 2000 Oct 11         |
| Ark 564      | IRTF       | ...                        | 8000–24000   | 2400              | 2000 Oct 11         |
| Mrk 335      | IRTF       | ...                        | 8000–24000   | 1800              | 2000 Oct 11         |
| Mrk 1044     | IRTF       | ...                        | 8000–24000   | 1200              | 2000 Dec 28         |
| S180         | IRTF       | ...                        | 8000–24000   | 2400              | 2000 Oct 11         |
| NGC 863      | IRTF       | ...                        | 8000–24000   | 1200              | 2000 Dec 28         |
1024 × 1024 CCD detector and a REOSC spectrograph. A 300 line mm\(^{-1}\) grating with blaze angle near 5500 Å and a spatial scale of 0′′.95 pixel\(^{-1}\) was used, giving an instrumental resolution ~8 Å. The slit, with a width of 2′′.5, was oriented in the east-west direction. Spectra were reduced with standard IRAF procedures (i.e., bias subtraction and flat-field division). The signal along the central 4 pixels was summed to extract the spectra. Wavelength calibration was carried out using HeNeAr arc lamps, with typical errors of less than 0.1 Å. Standard stars from Stone & Baldwin (1983) were used for flux calibration. In addition, a medium-resolution spectrum (≈3 Å) of 1H 1934 063, taken with that same telescope and covering the wavelength interval 6050–7600 Å, was also available. In the remainder of this text, we will refer to the spectrum of 1H 1934 063 taken with the 300 line mm\(^{-1}\) grating as the low-resolution spectrum and the one taken with the 600 line mm\(^{-1}\) grating as the high-resolution spectrum.

Ark 564 was observed in 1996 with the HST using the Faint Object Spectrograph (FOS) with a circular aperture 1″ in diameter. For this object, we retrieved the calibrated files from the HST data archive to obtain the wavelength, absolute flux, and error flags. A log of the optical observations is listed in Table 2.

2.4. Ultraviolet Spectroscopy

Ultraviolet spectra observed by the IUE and the HST (FOS and STIS) in the wavelength region around O\(^{+}\) λ1304 are available for all objects of the sample. The IUE spectra were re-extracted using the IUE New Spectral Image Processing System (NEWSIPS). When more than one observation for a given object was available, they were combined in order to produce a single, averaged spectrum. FOS and/or STIS nonproprietary archival calibrated files for Ark 564, Mrk 335, and Ton S180 were retrieved from the HST data archive. Ark 564 has been the subject of a monitoring campaign using STIS during the year 2000, so we averaged calibrated archival files taken between 2000 May and July. We compared the resulting spectrum with the FOS spectrum taken for this same object in 1996, and no significant difference was found in the region around λ1304. However, we preferred to work with the STIS spectrum because of the better resolution and signal-to-noise ratio (S/N), which
allowed us to separate, at a higher confidence level, the flux of O i $\lambda$1304 from that of Si ii $\lambda$1306. Table 3 shows the details of all UV observations used in this work.

Figure 2 show the composite near-IR, optical, and UV spectra for the galaxy sample. The arrows mark the position of the strongest O i lines that are of interest here.

2.5. Further Considerations

Before any analysis, the spectra were corrected for Galactic reddening using the values reported in Table 1. Although different apertures were used during the observations, this has little effect on the results reported here, since our analysis is restricted to lines emitted exclusively by the BLR. Table 4 lists the galaxy sample emission-line fluxes that will be used throughout this paper. The errors quoted reflect solely the uncertainty in the placement of the continuum, S/N around the line of interest and errors flags of the archival data and are 2 $\sigma$ significative. Fluxes were measured by fitting Gaussians to each emission feature. In all cases, O i/$\lambda$1304 ratio of either two lines that are of interest here.

Another source of error that may affect our results when combining data from different spectral regions, taken at different dates, is variability. It is widely known that Seyfert 1 galaxies are highly variable in the UV and optical continuum and broad emission lines. However, there is little infor-

## Table 3

Log of UV Observations

| Galaxy       | Instrument | Data Set    | Exposure (s)  | Coverage (Å) | Date (UT)       |
|--------------|------------|-------------|---------------|--------------|----------------|
| I H 1934−063 | IU/SWP     | SWP31894    | 8400.00       | 1200−2000    | 1987 Sep 21    |
| Ark 564..... | STIS       | O5T0010     | 1201.00       | 1150−1714    | 2000 May 10    |
| STIS         | O5T02010   | 1021.00     | 1150−1714    | 2000 May 14  |
| STIS         | O5T03010   | 1021.00     | 1150−1714    | 2000 May 19  |
| STIS         | O5T04010   | 1021.00     | 1150−1714    | 2000 May 24  |
| STIS         | O5T44010   | 1201.00     | 1150−1714    | 2000 Jul 6   |
| STIS         | O5T45010   | 1201.00     | 1150−1714    | 2000 Jul 8   |
| STIS         | O5T46010   | 1021.00     | 1150−1714    | 2000 Jul 10  |
| Mrk 335..... | FOS        | Y29E0202T   | 13900.00      | 1150−1600    | 1994 Dec 16    |
| Mrk 1044.....| IU/SWP     | SWP56260    | 34080.00      | 1200−2000    | 1995 Dec 7     |
| Mrk 1044.....| IU/SWP     | SWP56319    | 13499.00      | 1200−2000    | 1995 Dec 20    |
| Ton S180.....| STIS       | O5SP01010   | 1260.00       | 1150−1714    | 2000 Jan 22    |
| NGC 863..... | IU/SWP     | SWP40591    | 9000.00       | 1200−2000    | 1991 Jan 14    |

## Table 4

Fluxes of Relevant Emission Lines\(^a\)

| Line          | IH 1934−063 | Ark 564 | Mrk 335 | Mrk 1044 | Ton S180 | NGC 863 | I Zw 1\(^b\) |
|---------------|-------------|---------|---------|----------|----------|---------|-------------|
| O i $\lambda$1304 | <18.0$^a$ | 2.00 ± 0.20 | 10.9 ± 1.0 | 13.6 ± 2.00 | 5.74 ± 0.7 | 6.70 ± 1.0 | <10.0       |
| H e $\lambda$1640 | <56.5 | 11.8 ± 0.70 | 63.0 ± 5.0 | 24.2 ± 3.6 | 7.15 ± 1.50 | 25.7 ± 4.0 | ...         |
| H e $\lambda$4686 | 7.00 ± 0.80 | 3.80 ± 0.20 | 31.0 ± 3.0 | 4.48 ± 0.5 | 1.21 ± 0.15 | ... | ...         |
| H $\beta$      | 41.83 ± 3.0 | 22.8 ± 0.8 | 76.5 ± 7.0 | 26.8 ± 2.0 | 14.5 ± 1.0 | ... | ...         |
| H $\alpha$    | 129.7 ± 5.0 | 92.3 ± 1.0 | 320 ± 10 | 67.4 ± 4.0 | 43.0 ± 2.0 | ... | ...         |
| O i $\lambda$8446 | 14.5 ± 1.0 | 4.40 ± 0.10 | 8.14 ± 0.5 | 4.96 ± 0.4 | 0.98 ± 0.10 | 4.01 ± 0.30 | 8.83 ± 1.0 |
| O i $\lambda$1287 | 6.91 ± 0.24 | 2.70 ± 0.07 | 3.87 ± 0.17 | 1.52 ± 0.17 | 0.80 ± 0.09 | 1.65 ± 0.2 | 5.00 ± 0.4 |
| O i $\lambda$3165 | <0.17 | <0.18 | <0.20 | <0.22 | ... | ... | ...         |

\(^a\) In units of 10$^{-14}$ ergs cm$^{-2}$ s$^{-1}$.

\(^b\) Fluxes taken from Rudy et al. 2000.

\(^c\) The “less than” sign implies an upper limit.

\(^d\) In Ton S180 and NGC 863 O i $\lambda$13165 falls within an atmospheric absorption band, so it is not possible to derive an upper limit.
Information in the literature about optical and/or UV variability in NLS1s, even though they show the fastest variations in the soft and hard X-ray bands. Giannuzzo & Stirpe (1996) systematically monitored a sample of 12 NLS1 during a period of 1 yr and found that 10 of them showed significant variations in the optical continuum and permitted lines. Ark 564 and Mrk 1044, two of the objects from our sample included in Giannuzzo & Stirpe’s study, showed variations of ~9% and ~10%, respectively, in permitted lines H<sub>α</sub> and H<sub>β</sub>. More recent data for Ark 564 derived from a 2 yr optical monitoring program (Shemmer et al. 2001) showed that H<sub>β</sub> exhibited only minor variability (~3%) and that H<sub>α</sub> did not vary significantly. In the UV region, Collier et al. (2001), using STIS data taken from an intensive 2 month monitoring campaign, found flux variations of about 1% amplitude in the Ly<sub>α</sub> emission line. Moreover, they checked archival IUE observations of Ark 564 taken in 1984 January and compared these data with that of STIS. They found that the continuum and emission-line fluxes are in qualitative agreement in spite of the long span of the observations.

For Ton S180, we have compared archival IUE spectra taken in 1992 and 1993 with that of STIS used in the present work. Although the continuum from IUE presents a shift toward larger flux values (in a constant amount) relative to the STIS spectrum, the line fluxes shows very little difference (by less than a factor of 10%) between the two set of observations. In addition, our flux measurement for H<sub>β</sub> taken in 2000 is in perfect agreement with that reported by Winkler (1992), ruling out significant variations for that object.

Mrk 335 was monitored continuously in the optical region during a 7 yr campaign (Kasebaum 1997). This NLS1 shows significant variability in the continuum as well as in the emission lines H<sub>β</sub> and He ii λ4686 with rms fluctuation amplitude relative to the mean spectrum of 8.5%, 7%, and 18.8%, respectively. No UV variability data for this object have been reported. For 1H 1934–063 and NGC 863...
3. EXCITATION MECHANISMS OF THE O i LINES

O i λ8446 can be produced by four known mechanisms: recombination, collisional excitation, continuum fluorescence, and Lyβ fluorescence. Grandi (1980) and Rudy et al. (1989, 1991) gave a complete review of these four processes. For this reason, here we will only focus on the resulting O i emission lines arising from each of them.

Besides O i λ8446, recombination and collisional excitation also form O i λλ7774, while continuum fluorescence forms O i λλ7002, 7524, and λ13165. Lyβ fluorescence, also known as Bowen fluorescence, does not produce either of the last four lines; their absence is a good indicator of the predominance of this mechanism. Lyβ fluorescence takes advantage of the near coincidence of the energy levels of Lyβ (1025.72 Å) and the 2p 3p − 3d 3D0 transition of O i at 1025.77, as can be seen in Figure 3. At 10^4 K, a typical temperature within the BLR, the difference in wavelength falls within the Doppler core of Lyβ. When excitation to the 3d3D0 occurs, the O i electron may return directly to the ground state or otherwise suffer a series of transitions producing photons at λλ1287, λ8446, and λ1304 before arriving at the ground state.

Until now, Lyβ fluorescence has been the favored mechanism for the production of λ8446 in AGNs (Oke & Shields 1976; Grandi 1980; Morris & Ward 1989; Rudy et al. 1989). The reason for this conclusion has been the apparent lack of detection of additional O i transitions such as λ7002 and λ7774. However, weak broad features in low-resolution spectra tend to be smeared out when the nuclear continuum is strong and the S/N low. A direct confirmation of the predominance of the Bowen fluorescence can be obtained by measuring the photon flux ratio between λ11287 and λ8446, which must be unity (assuming no internal reddening). Lower values would indicate the presence of one of the other three mechanisms mentioned above, or some combination of these. This test has been elusive in AGNs for many years because of the lack of suitable observations and detectors in the near-IR. To the best of our knowledge, the only detection of O i λ11287 to date in an AGN has been for the prototype NLS1 I Zw 1.

Nonetheless, we find an inconsistency in the published data. Rudy et al. (1989) provided a direct confirmation of the Bowen mechanism in I Zw 1 by deriving an O i λ11287/λ8446 photon flux ratio of 1.02. Using more recent and higher quality data, taken at a higher resolution by Rudy et al. (2000) for the same object, we derive a photon flux ratio of 0.76 using the emission-line flux reported by those authors in their Table 1. Rudy et al. (1989) combine data taken at different times with a different instrumental setup and resolution, while in Rudy et al. (2000), both lines are observed simultaneously, with a superior quality spectrograph. Our estimate implies that in I Zw 1, contrary to what was previously found, O i λ8446 is formed by more than one process.

Table 5 lists, in the second column, the O i λ11287/λ8446 (hereafter ROIuv) flux ratio and, in the third column, the photon flux ratio of these two lines, derived for the objects in our sample. Only in Ton S180 and Ark 564, does the observational evidence point to Lyβ fluorescence as the dominant mechanism for the production of λ8446 since the photon flux ratio is near unity. But in Mrk 1044, for example, Lyβ fluorescence accounts for only ~40% of the observed λ8446. Evidently, additional excitation mechanisms that enhance O i λ8446 relative to λ11287 are at work. Reddening cannot be invoked to explain this discrepancy.

| Galaxy       | ROIuv Flux | ROIuv Photon | ROIuv Flux | ROIuv Photon |
|--------------|------------|--------------|------------|--------------|
| 1H 1934−063  | 0.48 ± 0.04 | 0.64 ± 0.05  | 1.25a     | 0.19a        |
| Ark 564      | 0.61 ± 0.02 | 0.82 ± 0.03  | 0.45 ± 0.05 | 0.07 ± 0.01  |
| Mrk 335      | 0.48 ± 0.04 | 0.64 ± 0.05  | 1.33 ± 0.15 | 0.20 ± 0.02  |
| Mrk 1044     | 0.31 ± 0.04 | 0.42 ± 0.05  | 2.78 ± 0.47 | 0.43 ± 0.07  |
| Ton S180     | 0.81 ± 0.12 | 1.08 ± 0.16  | 5.88 ± 0.98 | 0.91 ± 0.15  |
| NGC 863      | 0.41 ± 0.06 | 0.55 ± 0.08  | 1.70 ± 0.28 | 0.26 ± 0.04  |
| I Zw 1       | 0.56 ± 0.08 | 0.76 ± 0.11  | 1.14a     | 0.18a        |

* Upper limit.
because its net effect is the opposite: to reduce O i λ8446 relative to λ11287. If the line ratios in Table 5 are affected by reddening, after correcting for this effect they will appear even smaller.

It may be argued that the deficit of λ11287 photons can be due to strong, sharp, atmospheric absorption lines not readily apparent in low-resolution spectra. If such a line falls near λ11287 (in the Earth-frame wavelength), it can substantially affect the measured flux of the latter. Kingdon & Ferland (1991) addressed this possibility in their study of He i λ10830 in planetary nebulae and concluded that this effect could reduce the intensity of He i λ10830 by as much as 20%–25%. Nonetheless, as he stressed, the effect can be dramatic in sharp-lined objects such as H ii regions and planetary nebulae. For the particular case of O i λ11287, this line is spread over at least 21 pixels (the narrowest full width at zero intensity measured for O i λ11287) and located in different regions of the CCD owing to the different redshifts of the objects.

We consider that for O i λ11287, the most serious effect is not due to strong, sharp, atmospheric absorption lines but broad atmospheric bands located blueward of λ11287. If they are not adequately cancelled out after dividing the object’s spectrum by that of the telluric star, the shape and flux of the line can be seriously affected. Figure 4 shows, for every object, the observed spectrum, the spectrum of the telluric star observed at similar air mass, and the resulting spectrum after the division, in the region around O i λ11287. Note that in all cases the atmospheric features were cleanly removed. Although some residuals may be present, in no way do they affect the flux of λ11287. Also, the fact that the shape and width of λ11287 is essentially the same as that of λ8446 (see Rodriguez-Ardila et al. 2002) confirms that the deficit of photons in O i λ11287 cannot be due to this effect. Regarding λ8446, the position where it falls is far from any atmospheric absorption feature. The nearest one is located redward of 9000 Å (in the Earth-frame wavelength), while for the galaxy with the largest redshift (Ton S180), O i λ8446 is located at 8970 Å.

4. DISCUSSION

The results obtained in the last section provide, for the first time, strong evidence that Lyβ fluorescence cannot be the only process responsible for the observed strength of O i λ8446 in most AGNs of our sample. In order to study which of the remaining three mechanisms already mentioned (continuum fluorescence, recombination, and collisional ionization) are also producing λ8446, we use other permitted lines of O i as diagnostics tools.

According to Grandi (1980), continuum fluorescence can be probed by the presence of O i lines such as λ7254, λ7002, and λ13165. The later line is, in fact, a very good test because it should be one of the strongest ones, with a strength similar to that of λ11287, if that process is present. Unfortunately, observing λ13165 is not always easy. Depending on the radial velocity of the galaxy, it may fall very near or within a strong atmospheric band located between 13300 and 14150 Å, preventing its observation.

We have searched carefully in the spectra for the presence of O i λ13165. No conclusive evidence of this line was found in any galaxy. Upper limits derived for its flux are listed in Table 4. In all cases, it is detected at a limit of less than 0.1Fλ11287. In Ton S180 and NGC 863 it is not observable at all because it falls within a region of poor transmission. We also searched for O i λ7002 and λ7254 in 1H 1934–063. In the high-resolution spectrum of this object, the former line is clearly present, as can be seen in Figure 5. For the latter line, an upper limit for its flux was derived. Table 6 lists the values found. For Ark 564, no trace of λ7002 can be seen in the spectrum published by Comastri et al. (2001).

The lack of additional O i lines that should be observed if continuum fluorescence is also responsible for λ8446 emission and, most importantly, the very low upper limit measured to O i λ13165 leads us to conclude that this mechanism, although probably present, cannot be responsible for the observed excess of O i λ8446 emission.

Recombination is another excitation mechanism that could help to explain the strength of O i λ8446. However, this process produces numerous lines located in the visible region, arising from triplet and quintet configurations, in proportions corresponding to the ratio of their statistical weights (Grandi 1975). This implies that some of the additional O i lines should have comparable or larger intensities than O i λ8446. In 1H 1934–063, for which we have complete wavelength coverage from 0.37 to 2.4 μm, the only quintet line of O i detected at 3 σ level is λ7774 (3p5S–3p5P). This line is the quintet counterpart of O i λ8446. Its predicted relative intensity, assuming recombination as the excitation mechanism, should be λ7774/λ8446 ~ 1.7 (Grandi 1980). That value is 40 times higher than the observed one (λ7774/λ8446 ~ 0.07; see Table 6). For this object, if we subtract the fraction of the O i λ8446 flux produced by Lyβ fluorescence, the resulting λ7774/λ8446 ratio is 0.2, nearly 20 times weaker than its theoretical prediction.

The other object for which observations around O i λ7774 are available is Ton S180. The upper limit derived for this feature, also listed in Table 6, is 2 orders of magnitude weaker than the theoretical prediction. However, it is not

### Table 6

**Fluxes Measured to Other O i Features**

| Line     | 1H 1934–063 | Ark 564 | Mrk 335 | Mrk 1044 | Ton S180 |
|----------|-------------|---------|---------|----------|----------|
| λ6046... | <4.6        | <1.5    | <2.3    | <2.4     | <0.9     |
| λ6726... | <6.0        | ...     | <2.1    | <1.3     | ...      |
| λ7002... | 4.0 ± 0.8   | ...     | ...     | ...      | ...      |
| λ7254... | <3.9        | ...     | ...     | ...      | ...      |
| λ7774... | 10.0 ± 0.8  | ...     | ...     | <0.8     | ...      |
| λ7969... | 5.1 ± 0.9   | ...     | ...     | ...      | <0.9     |
| λ8446... | 145.0 ± 10  | 44.0 ± 1.0 | 81.4 ± 5.0 | 49.6 ± 5.0 | 9.8 ± 1.0 |

*In units of 10^{-15} ergs cm^{-2} s^{-1}. Lines with the < sign indicate an upper limit.*
expected that this line be strong in Ton S180 since Lyβ fluorescence accounts for the total O\textsc{i} λ8446 emission.

In addition to O\textsc{i} λ7774, we detect in 1H 1934–063, O\textsc{i} λ7990 (see Fig. 5) and λ6048. A blip at this later position is also observed in the spectrum of Ark 564. Nonetheless, their intensities are always a few percent of O\textsc{i} λ8446. For this reason, we conclude that recombination is certainly present, but it cannot explain alone the excess of λ8446 observed in most of the objects.

The only possibility that remains to be explored is collisional excitation by electrons. Grandi (1980) states that if this mechanism is operating, the predicted O\textsc{i} λ7774/λ8446 ratio would be 0.3. That value is near the observed ratio (0.2) derived in 1H 1934–063 after removing the contribution of Lyβ fluorescence for O\textsc{i} λ8446. The lack of observations around λ7774 for the remaining objects prevent us from drawing definite conclusions. However, our data clearly show that Lyβ fluorescence cannot be considered any longer as the single dominant mechanism for the production of the observed O\textsc{i} lines in AGNs. For 1H 1934–063, for instance, collisions may contribute up to 35% of the observed O\textsc{i} λ8446 flux.

Fig. 4.—Effect of the atmospheric absorption on O\textsc{i} λ11287. For each galaxy, (a) shows the observed spectrum in the region around that line, in Earth-frame wavelength coordinates. The arrow marks the centroid of λ11287. In (b) is plotted a sample of the atmospheric transmission in the same spectral region of (a), obtained from the spectrum of a telluric standard near the object’s position and observed at a similar air mass; (c) shows the spectrum of the object divided by that of the star. Note that most conspicuous atmospheric features disappeared.
4.1. *An Optically Thick $\lambda 1304$ Line?*

If collisional excitation is responsible for the excess of $\text{O } i \lambda 8446$ emission, in order for this process to be efficient the population of the level $3s^2S_0$ must be significant, i.e., above the Boltzmann population. This requires high optical depths in the $\lambda 1304$ line. Kwan & Krolik (1981) state that with increasing column density, trapping of $\lambda 1304$ becomes important in sustaining the population in $3s^2S_0$, and $\lambda 8446$ becomes optically thick. Trapping of $\lambda 8446$, in turn, builds up the population in $3p^3P_0$, eventually leading to trapping of $\lambda 11287$. As a result, the growth of these lines is subsequently quenched; once $\lambda 11287$ is optically thick, all three lines grow only logarithmically with optical depth. This possibility has been examined by Ferland & Persson (1989), who found that the very high column densities ($>10^{24.5} \text{ cm}^{-2}$) necessary to produce Ca $\text{ii}$ can produce large optical depths in the $\text{O } i$ lines. In fact, very recently, Rodríguez-Ardila et al. (2002) found that the $\text{O } i$, Ca $\text{ii}$, and Fe $\text{ii}$ lines have very similar emission-line profiles, in both form and width. This is interpreted as a cospatial Ca $\text{ii}$ and O $\text{i}$ emitting regions, which probably share similar physical conditions.

An indication that $\lambda 8446$ is thick would be branching from its upper level to $3s^2S_0$ level by the $\text{O } i \lambda 7254$ line (Rudy et al. 1991). This line is very close to $[\text{S } ii]\lambda 6717, 6731$, a common doublet in Seyfert 1 galaxies, so if this pair of lines is present, it may mask the observation of $\text{O } i \lambda 6726$. We have searched our spectra in order to find evidences for $\lambda 6726$. Table 6 list the derived upper limits. In none of the four objects where this measurement was possible was the $\lambda 6726$ line present at a level greater than $0.04I(\lambda 8446)$. We conclude that the intensity of $\lambda 8446$ is not significantly altered by optical depth effects. Probably, after the upper $3p^3P_0$ level is significantly populated, the electrons are rapidly promoted to the upper $3S_0$ and $1D^0$ levels because of their close proximity in energy (less than 2 eV), producing the additional O $\text{ii}$ lines detected and increasing the flux of $\lambda 8446$.

4.2. *$\text{O } i$ as a Reliable Reddening Indicator for the BLR*

According to the Grotrian diagram of Figure 3, independent of the excitation mechanism, every $\lambda 8446$ photon should produce a $\lambda 1304$ photon. Theoretically, the photon flux ratio $\lambda 1304/\lambda 8446$ (ROI uv, hereafter) must be equal to unity except when reddening is present, in which case, it should be smaller. Kwan & Krolik (1981) found that the intrinsic ROI uv can vary from 1 to 0.63 even in the absence of reddening due to Balmer continuum absorption of $\lambda 1304$ photons and the production of $\lambda 8446$ by collisional excitation. Grandi (1983) describes three additional processes that may destruct $\lambda 1304$: (1) $\lambda 1304$ photons can photoionize $\text{H } i$ atoms that exists in the $n = 2$ state; (2) collisional deexcitation can destroy $\lambda 1304$ photons; and (3) the upper term of $\lambda 1304 (3s^2S_0)$ can decay to the metastable terms of the ground configuration via the semi forbidden lines $\text{O } i \lambda 1641$ and $\lambda 2324 (2p^4^1D^0–3s^2S^0$ and $2p^4^1S^0–3s^2S^0$, respectively). Grandi’s calculations show that up to half of the $\lambda 1304$ photons can be converted to $\text{O } i \lambda 1641$ before leaving the emission cloud.

Our data offer, for the first time, the possibility of evaluating, at least to first order, how efficient the destruction of the $\lambda 1304$ photons can be. The fifth column of Table 5 lists the ROI uv photon derived for the galaxies. It was determined...
assuming an intrinsic flux ratio of 6.5. Note that the uncertainties in this quantity are, in most cases, larger than the estimated error due to variability (see §2.5.1), meaning that the results are not at all affected by this effect. Except Ton S180, all objects show flux ratios significantly below the lowest theoretical limit derived by Kwan & Krolik (1981). Even if in all these objects the $\lambda 1304$ photons are severely affected by the destruction mechanisms described above, they are not sufficient to explain the break of the one-to-one photon relation between $\lambda 8446$ and $\lambda 1304$. Ton S180 is particularly interesting in this respect. We had already seen that it was the only galaxy where ROI$_{uv}$ pointed to Ly$\beta$ fluorescence as the dominant mechanism for producing $\lambda 8446$. ROI$_{uv}$ not only confirms this result but also indicates that the physical conditions of the O i gas is different for this object. Apparently, the optical depth effects that may affect the O i lines do not apply here.

The departure from the one-to-one photon relation can be interpreted as due only to reddening or the combined effects of reddening and the destruction mechanisms of $\lambda 1304$. The second and third columns Table 7 list the $E(B-V)$ inferred from the observed flux ratio. Values listed in the second and third columns assume an intrinsic values of ROI$_{uv}$ of 1 and 1.6, respectively (which translates into flux ratios of 6.5 and 4). The Galactic extinction curve of Cardelli, Clayton, & Mathis (1989) were employed in this calculation.

The $E(B-V)$ derived from the $\lambda 1304/\lambda 8446$ ratio points toward low values of reddening in the BLR of Seyfert 1 galaxies, except in Ark 564, which seems to be affected by a moderate amount of extinction. Ton S180, on the other hand, shows evidence of being reddenning free.

In order to compare the $E(B-V)$ derived from the O i lines with that predicted from other indicators, we have also calculated the reddening using the Balmer decrement $\Delta H\alpha /H\beta$ and the He ii $\lambda 1640/\lambda 4686$ ratio. The results are shown in the fourth and fifth columns of Table 7, respectively. An “N.A.” entry means that particular ratio was not available for measurement in the spectrum and the lack of any value means that the calculated ratio gave unphysically results (the theoretical values adopted were 3.1 for the Balmer lines and 7.2 for the He ii lines). Although the results of Table 7 are approximate, mainly because of the uncertainty involved in the knowledge of the intrinsic ratio of the Balmer decrement and the He ii lines for the BLR, it is encouraging to see that the agreement between the different reddening indicators for the same object are good to within 0.1 mag of uncertainty. In particular, for Ton S180 and Mrk 1044 the three indicators agree to very little or no reddening at all, while for Ark 564, they clearly confirm the presence of dust. The highest discrepancy is observed in 1H 1934–963. This result can be explained if we consider that the S/N of the UV spectrum is very low and just upper limits to the flux of the lines were derived.

It is also interesting to see that the values of $E(B-V)$ derived assuming an intrinsic $\lambda 1304/\lambda 8446$ flux ratio of 4 are closer to the ones derived using other indicators than if we assume an intrinsic ratio of 6.5 (except for Ton S180). This provides strong observational support to the hypothesis of $\lambda 1304$ photons being destroyed by Balmer continuum absorption and the formation of $\lambda 8446$ by collisional excitation. Although detailed modeling of the BLR is beyond the scope of this paper, it would be important to estimate how much the intrinsic $\lambda 11287/\lambda 8446$ ratio is affected by this latter effect. The data provided here is a good starting point to investigate the physics of the outer BLR.

### Table 7

| Galaxy       | ROI$_{uv}$ | $\Delta H\alpha /H\beta$ | $\Delta$ He ii $\lambda 1640/\lambda 4686$ |
|--------------|------------|----------------------------|---------------------------------------------|
| 1H 1934–963  | 0.23       | 0.15                       | 0.0                                         |
| Ark 564      | 0.36       | 0.26                       | 0.22                                        |
| Mrk 335      | 0.21       | 0.30                       | 0.34                                        |
| Mrk 1044     | 0.11       | 0.05                       | 0.06                                        |
| Ton S180     | 0.01       | 0.00                       | 0.05                                        |
| NGC 863      | 0.18       | 0.11                       | N.A.                                        |
| I Zw 1       | 0.24       | 0.17                       | N.A.                                        |

$^a$ The value in parentheses below the reddening indicator corresponds to the intrinsic ratio assumed.

5. SUMMARY AND CONCLUSIONS

Near-infrared, optical, and UV spectroscopy has been used to study the excitation mechanisms leading to the formation of permitted O i lines in Seyfert 1 galaxies. From the observed $\lambda 11287/\lambda 8446$ photon flux ratio, we found that in only one of seven galaxies is Ly$\beta$ fluorescence the single dominant process in the formation of O i $\lambda 8446$. This result clearly contradicts previous assumptions that Ly$\beta$ fluorescence is the only contributor for the formation of the O i lines in those objects. Continuum fluorescence is discarded as an additional mechanism owing to the very low O i $\lambda 8446$/H$\beta$ flux ratio measurement as well as the absence of other emission lines that should be present in the optical region. Recombination is not negligible, although its effect on the flux of $\lambda 8446$ seems to be no larger than a few percent. Collisional excitation offers a plausible explanation to enhance the strength of the O i $\lambda 8446$ relative to that of $\lambda 11277$, leading to the strong deviation from unity observed in the $\lambda 11287/\lambda 8446$ ratio. This conclusion is drawn from the presence of O i $\lambda 7774$ in 1H 1934–963. The strength of this line, relative to that of $\lambda 8446$, agrees with theoretical predictions assuming collisional excitation as responsible for the formation of $\lambda 7774$. In that object, up to 35% of the observed $\lambda 8446$ flux may arise through collisional pumping. Collisional excitation is also favored if $\lambda 1304$ is optically thick, as is suggested by the presence of strong Ca ii lines, which requires high column densities for their formation.

In the absence of reddening, the $\lambda 1304/\lambda 8446$ photon flux ratio may depart from its intrinsic value (from 1 to 1.6) because of several mechanisms that destroy the $\lambda 1304$ photons, as well as optical depth effects that favor collisional excitation of $\lambda 8446$. The agreement between the $E(B-V)$ of the BLR derived using different reddening indicators (among them, the ratio $\lambda 1304/\lambda 8446$) is improved if an intrinsic flux ratio $\lambda 1304/\lambda 8446$ of 4 is assumed, meaning that destruction effects for the $\lambda 1304$ line are, in fact, present. Our results points toward low to moderate reddening for the BLR.

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