THE NUCLEAR REGION OF NGC 7469
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ABSTRACT

We have made spectrophotometric observations of the nuclear and circumnuclear regions of the Seyfert 1 galaxy NGC 7469, and we analyze the dynamics and structure of the emission-line regions. In the nuclear region of NGC 7469, we found a broad, an intermediate, and a narrow line-emitting region. The broad lines (FWHM ≈ 7800 km s⁻¹) are formed within a distance R ≤ 0.05 pc from the central source. For the narrow-line region, there is a large range in electron density and a scheme of ionization structure. The circumnuclear stellar population consists mostly of very old stars, and at a distance R ≈ 8″ from the nucleus, we detected the presence of hot, young stars. The gas at R ≈ 8″ is nitrogen overabundant.

Subject headings: galaxies: individual (NGC 7469) — galaxies: nuclei — galaxies: Seyfert

I. INTRODUCTION

NGC 7469 is a spiral galaxy with a total magnitude $M_B = 12.8$ and is one of the galaxies with an active nucleus first studied by Seyfert (1943). For the past few years, several spectral regions of NGC 7469 have been extensively surveyed: X-rays (Marshall, Warwick, and Pounds 1981), ultraviolet and optical (De Bruyn and Sargent 1978; Peterson et al. 1982), infrared (Rieke 1978), and radio (Ulvestad, Wilson, and Sramek 1981).

Systematic $U$, $B$, and $V$ observations show that both the continuum and the emission lines vary in time scales ranging from days to years (Lyutyi 1973, 1977, 1979; Penston et al. 1974; Penfold 1979).

Its nuclear spectrum shows broad, very intense, and asymmetric emission lines (Westin 1984, 1985, hereafter We84 and We85). The presence of absorption features, notably Ca II λ3933 K, indicates contamination by the stellar population. The continuum intensity increases blueward, characteristic of a power-law contribution, with a very conspicuous UV bump. A circumnuclear ring of star formation was found from high resolution spectra. Outside the starlike nucleus, high- and low-excitation components were found by mapping the brightest emission lines. Radial expansion is observed for the first component, whereas the latter participates only in the galaxy rotation and is photoionized by hot stars (Wilson et al. 1986, hereafter Wi86).

The aim of this work is to investigate the structure of the nuclear and neighboring regions of NGC 7469 in terms of their dynamics and composition by means of the analysis of spectra in the optical region of NGC 7469.

This paper is structured as follows. In § II, we present the observations; the continuum, emission lines, and the kinematics of the nuclear region are analyzed in § III; in § IV, we discuss the emission-line regions; stellar population synthesis and metallicity of the circumnuclear regions are in § V; conclusions are in § VI.

II. OBSERVATIONS

Three spectra of the Seyfert 1 galaxy NGC 7469 were taken with the two-dimensional photon-counting detector “2D-

FRUTTI” attached to the Cassegrain focus of the 1 m telescope of the CTIO (Cerro Tololo Inter-American Observatory) on 1986 September 2–5. The slit width was 8″. One spectrum was obtained positioning the slit on the starlike nucleus and summing pixel rows corresponding to 15″ along the slit; the other two were extracted summing pixel rows corresponding to 8″ centered at 5″ north and 8″ south of the nucleus, respectively (Fig. 1). The spectra were reduced using the standard spectrophotometric program TV-RED and were flux calibrated with stars from the catalog “Southern Spectrophotometric Standards” of Stone and Baldwin (1983). The final resolution achieved for these spectra, as estimated from the comparison lamp lines, is of the order of 300 km s⁻¹ (FWHM = 5 Å) around $\lambda = 5000$ Å.

The data were corrected for redshift adopting a radial velocity $V_r = 4626$ km s⁻¹ as measured from the average value calculated for the narrow forbidden emission lines.

The reddening correction was carried out assuming the interstellar extinction curves given by Seaton (1979) and applying the expression $F_\nu(\lambda) = F(\lambda)I^{10^{-0.4(V-V)}}\lambda^{[(V-K)/2.5]}$, where $X(\mu)$ is the extinction function and $\mu = 1/\lambda$, with $\lambda$ expressed in microns. $X(\mu)$ was expressed as a third-order polynomial fitted to the points of $X(\mu)$ given by Nandy et al. (1975). We adopted a color excess $E(B-V) = 0.14$ corresponding to the galactic and internal extinctions to deredden the spectra (We84, We85).

III. THE CONTINUUM AND THE EMISSION LINES

a) The Continuum

The stellar contribution was estimated assuming that the absorption spectrum observed at 5″ north of the nucleus represents the average stellar population present in the nuclear region. After subtraction of the emission features from the 5″ north spectrum, the resulting purely absorption spectrum was scaled to 3% of the nuclear spectrum at 5300 Å and then successively subtracted until the nuclear absorption line Ca II λ3933 K disappeared.

A power law ($F_\nu \propto \nu^{-n}$) was fitted to the continuum already free of the stellar contribution in the spectral range $\lambda > 4000$ Å (Fig. 2), and the best result was obtained with $n = 1.0 \pm 0.2$, a typical value for the nonthermal continuum of Seyfert 1 galaxies (Grandi and Phillips 1980; We85; Ferland and

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Osterbrock (1987). In the region $\lambda < 4000$ Å, the observed continuum clearly shows an excess over the power-law extrapolation. The stellar, nonthermal, and UV-excess contributions to the observed continuum at three different regions, 3850, 4200, and 5300 Å, are listed in Table 1. For $\lambda > 4200$ Å, the continuum is almost entirely due to the contribution of both the stellar and nonthermal components, but at 3850 Å, this contribution decreases to 78% and the excess dominates shortward of 3850 Å.

b) Emission-Line Spectrum

The lines were decomposed using Gaussian profiles by means of a nonlinear least-squares algorithm described in Bevington (1969). The convergence criterion was the minimization of the reduced chi-square $\chi^2$. Using Lorentz profiles as fitting functions always yielded greater $\chi^2$ than Gaussian profiles. Due to the very extended wings and intense core, the H I Balmer lines were fitted with three distinct Gaussian components each: a narrow one with FWHM $\approx 450$ km s$^{-1}$, an intermediate one with FWHM $\approx 2380$ km s$^{-1}$, and a broad one for the base with FWHM $\approx 7830$ km s$^{-1}$. The Gaussian components used to fit Hz were constrained to appear in the fit of the other H I lines with the same FWHM (km s$^{-1}$) as the corresponding component in Hz. [O III] $\lambda\lambda4959$, 5007 and [Ne III] $\lambda\lambda3869$, 3968 also show broad bases and intense cores and were fitted with two Gaussians. A blue asymmetry is observed in the base of the [O III] $\lambda\lambda4959$, 5007 pair, in opposition to the red asymmetry of the H I lines. The [O III] lines have been constrained to the theoretical ratio of 2.9. Figure 3 shows the result of this procedure for the H$\beta$ + [O III] region.

We present in Table 2 the intensity (or total flux) $I$, the FWHM, and the emission velocity $V_{em}$; the error ($\sigma$) in the intensity was estimated according to the noise level around each line.

The broad components of the H I Balmer lines exhibit a high emission velocity with a mean value of $\langle V_{em} \rangle = 1017 \pm 300$ km s$^{-1}$; the intermediate components of the H I lines and the broad components of [Ne III] $\lambda\lambda3869$, 3968 have $\langle V_{em} \rangle = 260 \pm 75$ km s$^{-1}$, whereas the broad components of [O III] $\lambda\lambda4959$, 5007 have a negative emission velocity $V_{em} = -150$ km s$^{-1}$. The narrow components of all the lines do not show any appreciable emission velocity.

![Power-law fit to the nuclear continuum of NGC 7469](image-url)
We present in Table 3 the contribution of each component to the total luminosity of the Balmer lines. It is interesting to point out that the intermediate component contributes about 50% for all the lines.

c) Kinematics of the Nuclear Region

The turbulence velocity $V_t$, defined as FWHM/1.67, is plotted in Figure 4 against $V_{em}$, showing a correlation that suggests the existence of three regions with different kinematic properties. The broad components are formed in a region close to the central ionizing source with the highest turbulence velocity ($V_t = 4690 \pm 31 \text{ km s}^{-1}$) and with $V_{em} = 1017 \pm 300 \text{ km s}^{-1}$. In the intermediate-line region (ILR), we measured $V_{em} = 260 \text{ km s}^{-1}$. The gas and dust present in the narrow-line region participate, on average, in the global rotation of the galaxy, as also shown by Wi86.

IV. DISCUSSION

Assuming that lines with similar FWHM values are emitted by gas with similar conditions, the decomposition of the emission lines in distinct components can be used to derive physical parameters for each emitting region.

a) BLR and ILR

For the broad and intermediate components, the Balmer decrement seems to be due mostly to recombination processes. As for the narrow component, this is also valid only assuming a strong absorption by dust, as shown in Figure 5. This fact allows one to estimate the BLR radius and the mass of ionized gas in the BLR and ILR (Osterbrock 1978).

Using the result that the H$\beta$ luminosity comes from recombination and $\langle N_e \rangle = 10^9 \text{ cm}^{-3}$ as a representative value of the electron density in the BLR (because no forbidden line is observed with FWHM similar to the broad H i lines), and $\langle N_e \rangle = 10^2-10^3 \text{ cm}^{-3}$ for the ILR ([Ne iii] and [O iii] have FWHM values similar to the intermediate H i components), then $14 < M_{BLR} < 1400$. The mass in the BLR can be estimated using $M_{BLR} = (N_e M_\odot + N_{H_2} M_{H_2}) V_e$ and $L(H\beta) = 2 N_e N_a (H\beta) V_e h(V(H\beta))$. With $97.14 \text{ Mpc}$ as the distance of NGC 7469 ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and a normal helium density $N_{H_2} = 0.1 N_e$, we have $M_{BLR} \approx 9.2 M_\odot$, and $130 < M_{ILR} < 13,000 M_\odot$. From the variability of the O iv $\lambda 1549$ line (We84, We85) and assuming spherical symmetry, we derive $R_{BLR} \approx 6.2 \times 10^{16} \text{ cm}$, and with the above mass estimate, $\epsilon \approx 10^{-3}$.

b) NLR

De Robertis and Osterbrock (1984) showed that for many high-ionization Seyfert nuclei, there exist good correlations between emission-line width with the ionization potential (IP) and with the critical density for de-excitation ($N_e$). In Figures 6 and 7, respectively, we plotted FWHM against IP and FWHM against log ($N_e$) for the narrow lines. These figures imply that the NLR of NGC 7469 is formed by a series of clouds of gas, each of which has a wide range of ionization zones, but in which the denser clouds are, on average, closer to the central ionizing source and move with a larger velocity dispersion than the less dense ones. For the ILR, a strong correlation of FWHM and log ($N_e$) was found.

For the low-ionization species, the electron density was obtained using the observed line ratios [S ii] $\lambda 6717/\lambda 6731$, [S ii] $\lambda 4068, 76/\lambda 6717, 31$, and [N ii] $\lambda 6548, 84/\lambda 5755$ (Table 2), together with the theoretical curves for these line ratios given by McCall (1984) (Fig. 8), and assuming a canonical electron temperature $T_e = 10^4 \text{ K}$; we found, respectively, $N_e = (7.1 \pm 0.2) \times 10^2 \text{ cm}^{-3}$, $(2.7 \pm 0.2) \times 10^3 \text{ cm}^{-3}$, and $(9.4 \pm 1.4) \times 10^5 \text{ cm}^{-3}$. Thus, for these ions, the electron density is in the range $700 \leq N_e \leq 10^5 \text{ cm}^{-3}$.

Density has also been derived from the [O iii] lines considering two cases: (a) [O iii] $\lambda 4363$ also has a broad component

![Figure 3](https://example.com/figure3.png)

**FIG. 3.**—Gaussian decomposition of the H$\beta +$ [O iii] profile; two components were used to fit each line of the pair [O iii] $\lambda\lambda 4959, 5007$
but it cannot be detected; using only the narrow components in the ratio \( R = [\text{O} \text{ III}] \lambda \lambda 4959, 5007/\lambda 4363 \), we found \( N_e = (2.1 \pm 0.3) \times 10^6 \text{ cm}^{-3} \); and (b) the two components of \([\text{O} \text{ III}] \lambda \lambda 4959, 5007\) and the one of \([\text{O} \text{ II}] \lambda 4363\) are emitted by gas with, on average, similar conditions, then \( N_e = (1.2 \pm 0.1) \times 10^6 \text{ cm}^{-3} \). Under the conditions of case (b), the observed ratio \( R \approx 35 \) cannot be reproduced for \( N_e < 10^6 \text{ cm}^{-3} \) unless \( T_e > 18,000 \text{ K} \), a value too high for the NLR of Seyfert 1 galaxies (Filippenko and Halpern 1984). This situation is more critical in case (a). The critical density of \([\text{O} \text{ III}] \lambda 4363\) is \( 3.3 \times 10^7 \text{ cm}^{-3} \), whereas for \([\text{O} \text{ III}] \lambda \lambda 4959, 5007\ N_e = 7.9 \times 10^5 \text{ cm}^{-3} \). In fact, \([\text{O} \text{ III}] \lambda 4363\) is broader than \([\text{O} \text{ III}] \lambda \lambda 4959, 5007\) by about 100 km s\(^{-1}\), implying that \( N_e \geq 10^5 \text{ cm}^{-3} \) in the clouds that produce most of the \([\text{O} \text{ II}] \lambda 4363\), whereas \( N_e \leq 10^6 \text{ cm}^{-3} \) in the clouds that produce most of the \([\text{O} \text{ III}] \lambda \lambda 4959, 5007\). Also, gas with \( N_e \geq 10^7 \text{ cm}^{-3} \) must enhance the Balmer lines relative to \([\text{O} \text{ III}] \lambda \lambda 4959, 5007\, because the \( N_e \) value for the Balmer lines is much higher. The ratio \([\text{O} \text{ III}] \lambda \lambda 4959, 5007/\text{H}\beta \approx 5\) is much smaller than the typical range 10–20 usually found in NLR of Seyfert 1 galaxies (Koski 1978).

The above results clearly show that the density in the NLR of NGC 7469 varies from \( N_e \approx 700 \text{ cm}^{-3} \) up to \( N_e \approx 10^7 \text{ cm}^{-3} \), and they also give support to the idea of an ionization structure for the NLR.

### Table 3

<table>
<thead>
<tr>
<th>RELATIVE CONTRIBUTION OF BALMER COMPONENTS</th>
<th>Line</th>
<th>Broad</th>
<th>Intermediate</th>
<th>Narrow</th>
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<td>48</td>
<td>24</td>
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<td>H(\beta)</td>
<td>37</td>
<td>51</td>
<td>12</td>
<td></td>
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<tr>
<td>H(\gamma)</td>
<td>36</td>
<td>54</td>
<td>10</td>
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<td>H(\delta)</td>
<td>36</td>
<td>57</td>
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### Table 4

<table>
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<th>LINE</th>
<th>5° NORTH (Å)</th>
<th>8° SOUTH (Å)</th>
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</thead>
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<tr>
<td>H(\alpha)</td>
<td>23835</td>
<td>6.93</td>
</tr>
<tr>
<td>Ca II 3933 K</td>
<td>3933</td>
<td>6.70</td>
</tr>
<tr>
<td>H + Ca II 3970 H</td>
<td>3970</td>
<td>6.92</td>
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<tr>
<td>H(\alpha) 4861</td>
<td>4861</td>
<td>2.97</td>
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<tr>
<td>G band 4300</td>
<td>4300</td>
<td>2.97</td>
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</table>

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V. CIRCUMNUCLEAR REGIONS

Spectroscopic, IR, and radio observations of the outer regions of NGC 7469 show the existence of an extended high-ionization gas component surrounded by a ring of H II regions at a distance of about 10" from the nucleus (Wi86). We use our off-nuclear spectra to add new information on the stellar population and metallicity of these regions.

The 5" north and 8" south spectra are clearly contaminated by the underlying stellar population (Fig. 1), which allows us to study the stellar content around the starlike nucleus. The equivalent width of the most prominent absorption lines (Table 4) together with the continuum shape were used to determine the corresponding stellar population templates, selected from a library built from star clusters spectra collected with IDS and CCD detectors at the ESO 1.5 and 2.2 m telescopes (for details, see Bica 1988 and references therein).

According to that synthesis model (S4), the stellar population contribution at 5870 Å to the 5" north spectrum is more than 80%, due to very old stars (>5 × 10⁶ yr), and the remaining contribution comes from intermediate and moderately young stars (>10⁸ yr). For the 8" south spectrum, the model template (S6) predicts a very old star contribution of 70% and an excess population of stars with 10⁶ < age < 10⁸ yr with respect to that at 5". In Figure 9, we show the 8" south spectrum, its template, and the subtraction. The maximum metallicity attained by the models is solar (Bica 1988).

After subtracting the templates, we measured the intensity of the emission lines on the pure emission spectra (Table 5). Intensity ratios plotted on the BPT diagrams (Baldwin, Phillips, and Terlevich 1981) unambiguously show that the 5" north region is photoionized by a power law and should be the high-excitation component that was also found in Wi86. The 8" south spectrum is typical of an H II region, in agreement with the young stellar population found in the population synthesis.

The metallicity of the 8" region was inferred from intensity ratios of the observed lines using the diagrams 13a and 13c in Dopita and Evans (1986). Using their Table 1, we found 12 + log (O/H) = 8.83, roughly the solar value, and we derive an N/O abundance log (N/O) = −0.85, nearly twice the solar value. In the diagram log (N/O) × 12 + log (O/H) in Pagel and Edmunds (1981), the position of the 8" H II region also indicates an N/O ratio above solar.

Basically, our results agree with those of Wi86 and are reinforced by the presence of a young stellar population as derived by the population synthesis and the finding that the gas in the 8" H II region is nitrogen enriched by secondary mechanisms.
Fig. 6.—Correlation between the FWHM (km s\(^{-1}\)) and IP for the narrow lines; the linear correlation is given by FWHM = 4.79 IP + 393.61, and the correlation coefficient is \(R^2 = 0.9\).

Fig. 7.—Correlation between the FWHM (km s\(^{-1}\)) and log \((N_e)\) for the narrow lines; the equation of the line is FWHM = 43.06 log \((N_e)\) + 288.33, and \(R^2 = 0.78\).

Fig. 8.—Relations between \(N_e\) and \(T_e\). Solid lines show the behavior of \(R = [\text{O III}] \lambda 4959, 5007/4363\); dotted line shows \([\text{N II}] \lambda 6548, 6584/5755\); short-dashed line shows \([\text{S II}] \lambda 6717/6731\); and long-dashed line shows \([\text{S II}] \lambda 4068, 4076/6717, 6731\). For the \([\text{O III}]\), we plot curves for the mean and the extreme values of \(R\).
NUCLEAR REGION OF NGC 7469

TABLE 5
OFF-NUCLEAR EMISSION-LINE PARAMETERS

<table>
<thead>
<tr>
<th>Ion</th>
<th>FWHM (km s⁻¹)</th>
<th>Flux (10⁻¹⁴ ergs cm⁻² s⁻¹)</th>
<th>FWHM (km s⁻¹)</th>
<th>Flux (10⁻¹⁴ ergs cm⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[O III]</td>
<td>3727</td>
<td>430</td>
<td>28 ± 3</td>
<td>605</td>
</tr>
<tr>
<td>[Ne III]</td>
<td>3869</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Hβ</td>
<td>4861</td>
<td>634</td>
<td>61 ± 3</td>
<td>389</td>
</tr>
<tr>
<td>[O III]</td>
<td>4959</td>
<td>579</td>
<td>29 ± 3</td>
<td>464</td>
</tr>
<tr>
<td>[O III]</td>
<td>5007</td>
<td>573</td>
<td>87 ± 4</td>
<td>460</td>
</tr>
<tr>
<td>[N II]</td>
<td>6548</td>
<td>537</td>
<td>90 ± 14</td>
<td>455</td>
</tr>
<tr>
<td>Hα</td>
<td>6562</td>
<td>379</td>
<td>377 ± 10</td>
<td>377</td>
</tr>
<tr>
<td>[N II]</td>
<td>6584</td>
<td>534</td>
<td>271 ± 14</td>
<td>452</td>
</tr>
<tr>
<td>[S II]</td>
<td>6717</td>
<td>223</td>
<td>48 ± 10</td>
<td>370</td>
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<tr>
<td>[S II]</td>
<td>6731</td>
<td>223</td>
<td>33 ± 10</td>
<td>370</td>
</tr>
</tbody>
</table>

This fact could be assigned to supermassive stars associated with star-forming events occurring during the last 10⁸ years.

VI. CONCLUSIONS

The main conclusions of our work can be summarized as follows. From the analysis of the emission lines, we found that in the nuclear region of NGC 7469, there exist at least three emission-line regions with distinct physical parameters, mainly the electron density and temperature. The BLR has a typical dimension of R ≈ 10¹⁷ cm. For the NLR and the ILR, we observed a strong correlation between the FWHM and N_e, which can be viewed as the result of an ionization structure scheme holding in these regions. The interval in electron density shows the coexistence of clouds spanning a large range in density in the NLR.

The circumnuclear stellar population consists mostly of very old stars (> 10¹⁰ yr) having superposed a conspicuous ring of stars younger than 10⁸ yr at R ≈ 8'. The presence of hot, young stars in these regions is further confirmed by dust emission in 3.3 μm (Cutri et al. 1984) and by the steep far-infrared continuum (Wi86). This picture is consistent with the emission spectra of gas still photoionized by the central source at R ≈ 5'', whereas hot stars photoionize the nitrogen-enriched gas at R ≈ 8''.

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