EXTENDED HIGH-IONIZATION NUCLEAR EMISSION-LINE REGION IN THE SEYFERT GALAXY
NGC 4051

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ABSTRACT

We present an optical spectroscopic analysis of the well-known Seyfert galaxy NGC 4051. The high-ionization nuclear emission-line region (HINER) traced by [Fe x] λ6374 is found to be spatially extended to a radius of 3″ (~150 pc) west and southwest from the nucleus; NGC 4051 is the third example that has an extended HINER. The nuclear spectrum shows that the flux of [Fe x] λ6374 is stronger than that of [Fe vii] λ6087 in our observation. This property cannot be interpreted in terms of a simple one-zone photoionization model. To understand what happens in the nuclear region in NGC 4051, we investigate the physical condition of the nuclear emission-line region in detail, using new photoionization models in which the following three emission-line components are taken into account: (1) optically thick, ionization-bounded clouds; (2) optically thin, matter-bounded clouds; and (3) a contamination component that emits Hβ and Hα lines. Here the observed extended HINER is considered to be associated with the low-density, matter-bounded clouds. Candidates for the contamination component are the broad-line region, the nuclear star-forming regions, or both. The complexity of the excitation condition found in NGC 4051 can be consistently understood if we take into account these contamination components.

Key words: galaxies: individual (NGC 4051) — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

It is known that Seyfert galaxies often show very high ionization emission lines, such as [Fe vii] λ6087, [Fe x] λ6374, [Fe xi] λ7892, and [Fe xiv] λ5303 (Oke & Sargent 1968; Grandi 1978; Penston et al. 1984; De Robertis & Osterbrock 1986). Because the ionization potentials of these lines are higher than 100 eV, much attention has been paid to the high-ionization nuclear emission-line region (HINER; Murayama, Taniguchi, & Iwasawa 1998, hereafter MT98; see also Binette 1985). The possible mechanisms of radiating such high-ionization emission lines are the following three processes: (1) collisional ionization in the gas with temperatures of Te ~ 10⁶ K (Oke & Sargent 1968; Nussbaumer & Osterbrock 1970); (2) photoionization by the central nonthermal continuum emission (Osterbrock 1969; Nussbaumer & Osterbrock 1970; Grandi 1978; Korista & Ferland 1989; Ferguson, Korista, & Ferland 1997b; Murayama & Taniguchi 1998a, 1998b, hereafter MT98a and MT98b, respectively); and (3) a combination of shocks and photoionization (Viegas-Aldrovandi & Contini 1989).

Recently, in context of the locally optimally emitting cloud models (LOC models; Ferguson et al. 1997a), Ferguson et al. (1997b) showed that the high-ionization emission lines can be radiated in conditions of a wide range of gas densities. More recently, MT98a found that type 1 Seyfert nuclei have excess [Fe vii] λ6087 emission with respect to type 2’s. Given the current unified model of active galactic nuclei (AGNs; Antonucci & Miller 1985; see for a review Antonucci 1993), the finding of MT98a implies that the HINER traced by the [Fe vii] λ6087 emission resides in the inner wall of such dusty tori. Since the covering factor of the torus is usually large (e.g., ~0.9), and the electron density in the tori (e.g., ~10⁷–10⁸ cm⁻³) is considered to be significantly higher than that (e.g., ~10³–10⁴ cm⁻³) of the narrow-line region (NLR), the contribution from the torus dominates the emission of the higher ionization lines (Pier & Voit 1995). Taking this HINER component into account, MT98b have constructed new dual-component (i.e., a typical NLR with a HINER torus) photoionization models and explained the observations consistently.

On the other hand, it is also known that some Seyfert nuclei have an extended HINER whose size can be up to ~1 kpc (Golev et al. 1995; MT98). The presence of such extended HINERs can be explained as the result of very low density conditions in the interstellar medium (nH ~ 1 cm⁻³) making it possible to achieve higher ionization conditions (Korista & Ferland 1989). Thus, MT98a suggested a three-component model for the spatial distribution of HINER in terms of photoionization; that is, (1) the inner wall of the dusty torus with electron densities of n_e ~ 10⁶–10⁷ cm⁻³; the torus HINER (Pier & Voit 1995; MT98b), (2) the innermost part of the NLRs; the NLR HINER (n_e ~ 10³–10⁴ cm⁻³) at a distance from ~10 to ~100 pc, and (3) the extended ionized region (n_e ~ 10⁰–10¹ cm⁻³) at a distance ~1 kpc (the extended HINER; Korista & Ferland 1989; MT98). Perhaps the relative contribution to the HINER emission from the above three components may be different from galaxy to galaxy. In particular, extended HINERs have been found only in NGC 3516 (Golev et al. 1995) and Tololo 0109–383 (MT98), and thus, it is important to investigate how common the extended HINER is in Seyfert galaxies.

In this paper, we report on the discovery of an extended HINER in the nearby Seyfert galaxy NGC 4051. This observation was made during the course of our long-slit
optical spectroscopy program for a sample of nearby Seyfert galaxies at the Okayama Astrophysical Observatory. Throughout this paper, we use a distance toward NGC 4051 of 9.7 Mpc, which is estimated using a value of $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a recession velocity of 726 km s$^{-1}$ (Ulvestad & Wilson 1984). Therefore, 1'' corresponds to 47 pc at this distance.

2. OBSERVATIONS

The spectroscopic observations were made at Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, on 1992 June 5. The New Cassegrain Spectrograph was attached to the Cassegrain focus of the 188 cm reflector. A $512 \times 512$ CCD with pixel size of 24 $\mu$m $\times$ 24 $\mu$m was used, giving a spatial resolution of 1.46 pixel$^{-1}$ by $1 \times 2$ binning. A 1.8 slit with a length of 300'' was used with a grating of 150 grooves mm$^{-1}$ blazed at 5000 Å. The position angle was set to 90°. The wavelength coverage was set to 4500–7000 Å. We took three spectra: (1) the central region, (2) 2'' north of the central region, and (3) 2'' south of the central region. Each exposure time was 1200 s. The slit positions for NGC 4051 are displayed in Figure 1. The data were reduced with the use of IRAF. The reduction was made with a standard procedure; bias subtraction and flat-fielding were accomplished with the data of the dome flats. The flux scale was calibrated by using a standard star (BD +33°2642). The nuclear spectrum was extracted with a 2''92 aperture. The seeing size derived from the spatial profile of the standard star was about 2''3 (FWHM) during the observations.

3. OBSERVATIONAL RESULTS

3.1. Emission-Line Properties of the Nuclear Spectrum

The spectrum of the nuclear region (the central 2''9 $\times$ 1''8 region) is shown in Figure 2. To estimate emission-line fluxes, we made multicomponent Gaussian fitting for the spectrum using the Spectro-Nebula graph (Kosugi et al. 1995) package. The identified emission lines of the nuclear region are summarized in Table 1. The $[\text{Fe} \text{x}] \lambda 6374$ emission line is blended with $[\text{O} \text{ i}] \lambda 6364$. Assuming the theoretical ratio of $[\text{O} \text{ i}] \lambda 6300/\lambda 6364 = 3$ (Osterbrock 1989), we measured the $[\text{Fe} \text{x}] \lambda 6374$ flux. The reddening was estimated by using the Balmer decrement (i.e., the ratio of narrow components of Hα and Hβ). If case B was assumed, an intrinsic value of the Hα/Hβ ratio was 2.87 for $T = 10^4$ K (Osterbrock 1989). However, Veilleux & Osterbrock (1987) mentioned that the harder photoionizing spectrum of AGNs results in a large transition zone or partly ionized region in which collisional excitation becomes important (Ferland & Netzer 1983; Halpern & Steiner 1983). The main effect of the collisional excitation is to enhance Hα. Therefore, we adopt Hα/Hβ = 3.1 for the intrinsic ratio, and accordingly, we obtain $A_V = 1.00$ mag. This value is almost consistent with the previous estimation ($A_V = 1.11$ mag; Erkens, Appenzeller, & Wagner 1997). In our observation, $[\text{Fe} \text{x} ] \lambda 6374$ (ionized potential 233.6 eV) is stronger than $[\text{Fe} \text{vii} ] \lambda 6087$ (99.1 eV). This observational result is inconsistent with the predictions of simple one-zone photoionization models (see § 4).

In Table 2, we give a comparison between our observational data and the previous sets (Anderson 1970; Grandi 1978; Yee 1980; Penston et al. 1984; Veilleux 1988; Erkens et al. 1997). Although Erkens et al. (1997) gave $[\text{Fe} \text{vii} ] \lambda 6087/[\text{Fe} \text{x} ] \lambda 6375 = 0.966$ in their paper, they recently rereduced their data and found that the true observed line ratio is 0.500 (S. Wagner & I. Appenzeller, personal communication).

![Fig. 1.—Slit positions we set for NGC 4051. Images are taken from the Digitized Sky Survey.](image1)

![Fig. 2.—Nuclear spectrum of NGC 4051](image2)
1999, private communication). Although [Fe VII] \( \lambda 6087 \) / [Fe X] \( \lambda 6374 \) in Veilleux (1988) is significantly larger than that in ours, our ratio is consistent with those in Penston et al. (1984) and Erkens et al. (1997). Although we do not fully understand the significant difference between Veilleux (1988) and the other observations, it may be due partly to the difference of slit width or aperture size among the observations.

NGC 4051 is one of the well-known Seyfert galaxies (Seyfert 1943). It has been mostly classified as a type 1 Seyfert (Adams 1977), while Boller, Brandt, & Fink (1996) and Komossa & Fink (1997) pointed out that the observational properties of NGC 4051 are similar to those of narrow-line Seyfert 1 galaxies (NLS1's; Osterbrock & Dahari 1983; Osterbrock & Petke 1985). Although our observational data show the broad component of H\( \alpha \) clearly, the broad component of H\( \beta \) is not detected. The results of deconvolution for H\( \alpha \) and H\( \beta \) are shown in Figures 3 and 4, respectively.

### 3.2. Spatial Distribution of the Emission-Line Region

In Tables 3A–3D, we give the emission-line properties of the off-nuclear regions: west (2.9 west), southeast (1.5 south, 2° west), southwest (1.5 south, 2° east), and east (2° east). Since the flux of [O I] \( \lambda 6300 \) in these areas is not measured because of the insufficient signal-to-noise ratio

### Table 1

**Emission-Line Data of the Nuclear Region in NGC 4051**

| Identification | \( \lambda_{\text{sys}} \) (Å) | FWHM* (km s\(^{-1}\)) | \( F(F/\text{H}_{\beta}) \) Line Ratio | 1 \( \sigma \) | \( I(I/\text{H}_{\beta}) \) Line Ratio | 1 \( \sigma \) |
|---------------|-----------------|------------------|-----------------|------|-----------------|------|
| H\( \beta \) | 4874.6 | 934.2 | 1.000 | f | 1.000 | ... |
| [O III] | 4970.7 | 431.3 | 0.457 | ±0.016 | 0.445 | ±0.015 |
| [O III] | 5018.7 | 427.1 | 1.348 | ±0.027 | 1.294 | ±0.026 |
| [Fe XIV] | ... | ... | <0.071* | ... | <0.063* | ... |
| He I | 5886.5 | 839.6 | 0.166 | ±0.014 | 0.130 | ±0.012 |
| [Fe II] | ... | ... | <0.080* | ... | <0.060* | ... |
| [O I] | 6314.2 | 453.7 | 0.156 | ±0.012 | 0.113 | ±0.009 |
| [O I] | 6377.2 | 449.2 | 0.052 | ±0.012 | 0.037 | ±0.009 |
| [Fe II] | 6387.4 | 762.7 | 0.190 | ±0.014 | 0.136 | ±0.011 |
| [N II] | 6562.1 | 458.9 | 0.409 | ±0.017 | 0.286 | ±0.014 |
| H\( \alpha \)N | 6577.4 | 666.3 | 4.351 | ±0.073 | 3.030 | ±0.075 |
| H\( \beta \)N | 6577.5 | 3439.7 | 2.285 | ±0.040 | 1.591 | ±0.035 |
| [N II] | 6597.4 | 456.4 | 1.208 | ±0.029 | 0.838 | ±0.028 |
| [S II] | 6733.5 | b | 0.187 | ±0.012 | 0.127 | ±0.009 |
| [S II] | 6747.9 | b | 0.201 | ±0.012 | 0.136 | ±0.009 |

* Corrected for the instrumental width.
* Corrected for the reddening-corrected relative intensities. We adopted \( A_{\nu} = 0.995 \). Accordingly, \( I(F/\text{H}_{\beta}) = 4.269 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2} \).
* Estimated 1 \( \sigma \) error for \( F(F/\text{H}_{\beta}) \).
* Estimated 1 \( \sigma \) error for \( I(I/\text{H}_{\beta}) \).
* Estimated 1 \( \sigma \) error for \( F(F/\text{H}_{\beta}) \).

b Narrower than the measurable limit (instrumental width).

### Table 2

**A Comparison of Our Data with Previous Data**

| Parameter | Anderson 1970 | Grandi 1978 | Yee 1980 | PFBBW* | Veilleux 1988 | EAW* | Ours |
|-----------|----------------|-------------|---------|--------|----------------|-----|-----|
| Date ...... | 66 ~ 67? | 1974? | 1974 Apr 21 | 1977 Apr 4 | 1978 Mar 25 | 1992 Jul | 1992 Jun 5 |
| Telescope ...... | Wilson 2.5 m | Lick 3 m | Hale 5 m | Hale 5 m | Lick 3 m | DSAZ* 2.2 m | OAO 1.8 m |
| Detector ...... | Photomultiplier | IRTS* | Photomultiplier | IPCS | IRTS* | CCD | CCD |
| Slit width ...... | Slitless | 2'7 | Slitless | ? | 2'7 | 1'5 | 1'8 |
| [O III] / [H\( \beta \)] ...... | 1.750 | ... | 2.399 | ... | ... | ... | 1.739 |
| [Fe II] / [H\( \beta \)] ...... | ... | 0.062 | ... | ... | ... | ... | <0.060 |
| [Fe II] / [Fe X] ...... | ... | ... | 0.490 | 1.000 | 0.500* | <0.441 |
| [Fe II] / [Fe X] ...... | ... | ... | 0.324 | ... | 0.514* | ... |

* Penston et al. 1984.
* Erkens et al. 1997.
* The Calar Alto Observatory (Spain).
* Image-tube scanner.
* [O III] \( \lambda 4959 + 5007 \) / [H\( \beta \) narrow].
* [Fe II] \( \lambda 6087 \) / [H\( \beta \) narrow].
* [Fe II] \( \lambda 6087 \) / [Fe X] \( \lambda 6374 \).
* [Fe X] \( \lambda 7892 \) / [Fe X] \( \lambda 6374 \).
* From U. Erkens, I. Appenzeller, & S. Wagner 1999, private communication.
(S/N), we do not subtract the flux of [O i] $\lambda$6364 from that of [Fe x] $\lambda$6374. Although we measured the fluxes of emission lines to the northeast, those data are not tabulated, because we could not detect the H$\beta$ unambiguously. The S/N of the northwest position is so poor that we did not measure the fluxes of emission lines.

Figure 5 shows that the HINER traced by [Fe x] $\lambda$6374 is extended westward up to 3$''$ (240 pc). This is more extended than the NLR traced by [O i] $\lambda$6300. Since, as shown in Figure 6, there is no strong line of sky emission at the observed wavelength of [Fe x], the extended [Fe x] appears to be real. Figure 5 also shows that the HINER may be extended southwestward. However, this may be due to the contamination from the nuclear region, suggested by the relatively broad width of H$\beta$ at the southwest position.

Following Veilleux & Osterbrock (1987), we investigate the excitation conditions of the emission-line region in each position. As shown in Figure 7, we find that the regions where [Fe x] is absent exhibit AGN-like excitations, whereas the regions where [Fe x] is found show H II region-like excitations (except for the southeast region, where the line ratios show H II region-like excitation, and the reddening-corrected relative intensities. We adopted $A_V = 1.000$.

**TABLE 3A**

| IDENTIFICATION | $\lambda$$_{line}$ (Å) | FWHM$^*$ (km s$^{-1}$) | $F/F$(H$\beta$/N)$^b$ | $I/I$(H$\beta$/N)$^c$ |
|----------------|------------------------|-----------------------|----------------------|----------------------|
| H$\beta$/N ...... | 4874.8                 | 677.1                 | 1.000                | 1.000                |
| [O i]          | 4970.7                 | 657.9                 | 0.563 $\pm$ 0.068   | 0.548 $\pm$ 0.066   |
| [O iii]        | 5018.7                 | 651.6                 | 1.660 $\pm$ 0.115   | 1.594 $\pm$ 0.111   |
| [Fe x]         | 6391.2                 | 765.9                 | 0.680 $\pm$ 0.075   | 0.488 $\pm$ 0.061   |
| [N ii]         | 6562.6                 | 771.2                 | 0.634 $\pm$ 0.075   | 0.442 $\pm$ 0.059   |
| H$\alpha$/N ...... | 6577.3                 | 769.5                 | 4.440 $\pm$ 0.271   | 3.087 $\pm$ 0.268   |
| [N ii]         | 6597.9                 | 767.1                 | 1.870 $\pm$ 0.128   | 1.296 $\pm$ 0.120   |
| [S ii]         | 6733.0                 | *                     | 0.268 $\pm$ 0.053   | 0.182 $\pm$ 0.038   |
| [S ii]         | 6747.4                 | *                     | 0.405 $\pm$ 0.056   | 0.274 $\pm$ 0.042   |

$^*$ Estimated 1 $\sigma$ error for observed line ratios.

$^b$ The reddening-corrected relative intensities. We adopted $A_V = 1.000$.

$^c$ Estimated 1 $\sigma$ error for $F$(H$\beta$/N) is $1.315 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$.

$^d$ Narrower than the measurable limit (instrumental width).
### Table 3B

**Emission-Line Data for the Off-nuclear Region (1.5 South, 2° West)**

| Identification | \( \lambda_{ab} \) (Å) | FWHM* (km s\(^{-1}\)) | \( F/\langle H\beta F \rangle \)^b | \( I/\langle H\beta F \rangle \)^f | Line Ratio | 1 \( \sigma \)Δ | Line Ratio | 1 \( \sigma \)Δ |
|----------------|-----------------|-----------------|-----------------|-----------------|--------|--------|-----------------|--------|
| H\(\beta\)N     | 4869.4          | 839.7           | 1.000           | 1.000           |        |        | 0.291          | 0.498  |
| [O iii]         | 4967.1          | 444.6           | 0.459 ± 0.031   | 0.443 ± 0.030   |        |        | 0.332          | 0.146  |
| [O iii]         | 5015.1          | 440.3           | 1.353 ± 0.052   | 1.285 ± 0.049   |        |        | 0.146          | 0.332  |
| He II          | 5886.6          | 832.6           | 0.226 ± 0.035   | 0.166 ± 0.026   |        |        | 0.166          | 0.332  |
| [Fe x]         | 6381.2          | 705.4           | 0.244 ± 0.027   | 0.159 ± 0.018   |        |        | 0.159          | 0.332  |
| [N ii]         | 6559.5          | 666.9           | 0.616 ± 0.032   | 0.388 ± 0.024   |        |        | 0.388          | 0.332  |
| HaN            | 6574.2          | 665.4           | 4.911 ± 0.160   | 3.083 ± 0.145   |        |        | 3.083          | 0.332  |
| [N ii]         | 6594.8          | 663.3           | 1.819 ± 0.064   | 1.137 ± 0.055   |        |        | 1.137          | 0.332  |
| [S ii]         | 6731.1          |                | 0.212 ± 0.022   | 0.129 ± 0.014   |        |        | 0.129          | 0.332  |
| [S ii]         | 6745.5          |                | 0.185 ± 0.021   | 0.112 ± 0.014   |        |        | 0.112          | 0.332  |

a Corrected for the instrumental width.
b \( F(H\beta F) = 4.378 \times 10^{-14} \) ergs s\(^{-1}\) cm\(^{-2}\).
c The reddening-corrected relative intensities. We adopted \( A_V = 1.280 \).
d Estimated 1 \( \sigma \) error for observed line ratios.
e Estimated 1 \( \sigma \) error for reddening-corrected line ratios.
f Estimated 1 \( \sigma \) error for observed line ratios.
g N Narrower than the measurable limit (instrumental width).

### Table 3C

**Emission-Line Data for the Off-nuclear Region (1.5 South, 2° East)**

| Identification | \( \lambda_{ab} \) (Å) | FWHM* (km s\(^{-1}\)) | \( F/\langle H\beta F \rangle \)^b | \( I/\langle H\beta F \rangle \)^f | Line Ratio | 1 \( \sigma \)Δ | Line Ratio | 1 \( \sigma \)Δ |
|----------------|-----------------|-----------------|-----------------|-----------------|--------|--------|-----------------|--------|
| H\(\beta\)N     | 4870.8          | 1220.2          | 1.000           | 1.000           |        |        | 0.291          | 0.498  |
| [O iii]         | 4967.0          | 589.4           | 0.406 ± 0.056   | 0.394 ± 0.055   |        |        | 0.394          | 0.332  |
| [O iii]         | 5015.0          | 583.8           | 1.196 ± 0.091   | 1.145 ± 0.087   |        |        | 1.145          | 0.332  |
| [N ii]         | 6559.4          | 674.7           | 0.627 ± 0.054   | 0.425 ± 0.045   |        |        | 0.425          | 0.332  |
| HaN            | 6574.2          | 673.2           | 4.566 ± 0.290   | 3.086 ± 0.279   |        |        | 3.086          | 0.332  |
| [N ii]         | 6594.7          | 671.1           | 1.849 ± 0.122   | 1.245 ± 0.115   |        |        | 1.245          | 0.332  |
| [S ii]         | 6729.7          |                | 0.245 ± 0.027   | 0.161 ± 0.021   |        |        | 0.161          | 0.332  |
| [S ii]         | 6744.1          |                | 0.287 ± 0.029   | 0.189 ± 0.023   |        |        | 0.189          | 0.332  |

a Corrected for the instrumental width.
b \( F(H\beta F) = 3.492 \times 10^{-14} \) ergs s\(^{-1}\) cm\(^{-2}\).
c The reddening-corrected relative intensities. We adopted \( A_V = 1.078 \).
d Estimated 1 \( \sigma \) error for observed line ratios.
e Estimated 1 \( \sigma \) error for reddening-corrected line ratios.
f Estimated 1 \( \sigma \) error for observed line ratios.
g N Narrower than the measurable limit (instrumental width).

### Table 3D

**Emission-Line Data for the Off-nuclear Region (2°9 East)**

| Identification | \( \lambda_{ab} \) (Å) | FWHM* (km s\(^{-1}\)) | \( F/\langle H\beta F \rangle \)^b | \( I/\langle H\beta F \rangle \)^f | Line Ratio | 1 \( \sigma \)Δ | Line Ratio | 1 \( \sigma \)Δ |
|----------------|-----------------|-----------------|-----------------|-----------------|--------|--------|-----------------|--------|
| H\(\beta\)N     | 4871.1          | 781.7           | 1.000           | 1.000           |        |        | 0.291          | 0.498  |
| [O iii]         | 4968.5          | 517.5           | 0.995 ± 0.148   | 0.979 ± 0.146   |        |        | 0.979          | 0.332  |
| [O iii]         | 5016.5          | 512.6           | 2.936 ± 0.338   | 2.864 ± 0.332   |        |        | 2.864          | 0.332  |
| [N ii]         | 6560.7          | 607.2           | 0.739 ± 0.132   | 0.594 ± 0.126   |        |        | 0.594          | 0.332  |
| HaN            | 6575.5          | 605.8           | 3.852 ± 0.436   | 3.092 ± 0.498   |        |        | 3.092          | 0.332  |
| [N ii]         | 6596.0          | 604.0           | 2.180 ± 0.261   | 1.747 ± 0.291   |        |        | 1.747          | 0.332  |

a Corrected for the instrumental width.
b \( F(H\beta F) = 1.720 \times 10^{-14} \) ergs s\(^{-1}\) cm\(^{-2}\).
c The reddening-corrected relative intensities. We adopted \( A_V = 0.604 \).
d Estimated 1 \( \sigma \) error for observed line ratios.
e Estimated 1 \( \sigma \) error for reddening-corrected line ratios.
f Estimated 1 \( \sigma \) error for observed line ratios.
g N Narrower than the measurable limit (instrumental width).
although [Fe x] is not detected). It is unlikely that the [Fe x] emission arises from H II regions. Therefore, the observed H II region–like excitations are due not to photoionization by massive stars but to some additional mechanism. We will discuss this complex property in § 5.

3.3. A Summary of the Observational Results

As noted in § 1, there are three kinds of HINER: (1) the torus HINER, (2) the NLR HINER, and (3) the extended HINER (see MT98a). Our detection of the extended [Fe x]-
emitting region tells us that the extended HINER exists at least in NGC 4051. Here we estimate how strong the contribution is from the torus HINER using the dual-component photoionization model of MT98b. According to the diagnostic diagram of their model (Fig. 2 in MT98b), we find that the torus HINER may contribute less than 3% to the total intensity of the HINER emission. On the other hand, if [Fe x] in the nuclear region was mainly attributed to the NLR HINER, this line would have a larger FWHM in the nuclear region than in off-nuclear regions, because the flux contribution of the NLR HINER may be negligibly small in the off-nuclear regions. Since we could not find a difference of FWHM of [Fe x] between the nuclear region and the west, the NLR HINER is not a dominant source in NGC 4051. It is therefore suggested that the majority of the HINER emission in NGC 4051 arises from low-density interstellar medium within a radius of $\approx 150$ pc.

4. PHOTOIONIZATION MODEL

To understand the nuclear environment of NGC 4051, we use photoionization models and compare the predictions of the models with the observed emission-line ratios of the nuclear region of NGC 4051. The simplest model for the NLRs of Seyfert galaxies is a so-called one-zone model, which assumes optically thick clouds of single density and NLRs of Seyfert galaxies is a so-called one-zone model, the nuclear region of NGC 4051. The simplest model for the tions of the models with the observed emission-line ratios of 

### Table 4

| LINE                  | FOS8, b | OPTICALLY THIN | SOLAR ABUNDANCE | DUSTY ABUNDANCE |
|-----------------------|---------|----------------|-----------------|-----------------|
| [Ne v] 3426           | 0.09    | 0.62           | 0.67            |                 |
| [O iii] $\lambda$5007 | 7.11    | 11.7           | 10.8            |                 |
| [Fe xiv] 23303        | *       | 0.03           | 0.003           | 0.004           |
| [Fe vii] $\lambda$6087| 0.02    | 0.049          | 0.009           |                 |
| [O i] 6300            | 0.85    | 0.56           | 0.84            |                 |
| [Fe x] 6374           | 0.002   | 0.015          | 0.002           |                 |
| [N ii] 6583           | 2.56    | 1.18           | 1.69            |                 |
| [S ii] $\lambda$6716 + 6731| 1.37    | 1.20           | 1.87            |                 |
| [Fe x] 7892           | *       | 0.068          | 0.008           |                 |

a Normalized by H$\beta$.
b Ferland & Osterbrock 1986.
c Ferguson et al. 1997.
d Assuming the abundance of the Orion Nebula (see FKBF97).
e Not predicted by their model.

4.1. A Two-Component Photoionization Model

We construct a two-component system for the nuclear emission-line region of NGC 4051. One component is optically thick, ionization-bounded clouds (IB clouds). This component emits mainly low-ionization emission lines, like clouds in typical NLRs. The other is optically thin, low-density, matter-bounded clouds (MB clouds; Viegas-Alfordandi 1988; Viegas-Alfordandi & Gruenwald 1988; Binette, Wilson, & Storchi-Bergmann 1996; Wilson, Binette, & Storchi-Bergmann 1997; Binette et al. 1997) that radiate high-ionization emission lines selectively. These MB clouds are expected to emit more intense [Fe x] $\lambda$6374 than [Fe vii] 6087, because their densities are assumed to be low enough to achieve very high ionization conditions ($\S$ 4.2).

Ionization and thermal equilibrium calculations have been performed with the photoionization code CLOUDY (version 90.04; Ferland 1996) to calculate the emission from plane-parallel, fixed hydrogen density clouds. Taking into account many lines of evidence in favor of a nitrogen over-abundance (Storchi-Bergmann & Pastoriza 1990; Storchi-Bergmann 1991; Storchi-Bergmann et al. 1998), we adopt twice the solar nitrogen abundance. Namely, all elements have solar values except for nitrogen. The detection of strong [Fe x] suggests that most iron remains in the gas phase, although the depletion of iron would be more serious than that of other elements (e.g., Phillips, Gondhalekar, & Pettini 1982). Therefore, internal dust grains in the NLR are not taken into account in our calculations. The shape of the ionizing continuum from the central engine is

$$f_{\nu} = \nu_{\text{UV}} \exp \left(\frac{-h \nu}{kT_{\text{IR}}} \right) \exp \left(\frac{-kT_{\text{IR}}}{h \nu} \right) + \nu \alpha_{\text{ox}}$$

We adopt the following parameters: (1) $kT_{\text{IR}}$ is the infrared cutoff of the so-called big blue bump component, and we adopt $kT_{\text{IR}} = 0.01$ ryd; (2) $T_{\text{BB}}$ is the temperature that parameterizes the big blue bump continuum, and we adopt a typical value, $1.5 \times 10^5$ K; (3) $\alpha_{\text{UV}}$ is the slope of the low-energy big blue bump component. We adopt $\alpha_{\text{UV}} = -0.5$. Note that the photoionization is not sensitive to this parameter. Also, (4) $\alpha_{x}$ is the slope of the X-ray component, and we adopt $\alpha_{x} = -1.0$. This power-law component is not extrapolated below 1.36 eV or above 100 keV. Below 1.36 eV, this term is set to zero, while above 100 keV, the continuum is assumed to fall off as $\nu^{-3}$. Finally, (5) the UV–to–X-ray spectral slope, $\alpha_{\text{ox}}$, is defined as

$$\alpha_{\text{ox}} = \frac{\log \left[ F_{\nu}(2 \text{ keV})/F_{\nu}(2500 \text{ Å}) \right]}{\log \left[ \nu(2 \text{ keV})/\nu(2500 \text{ Å}) \right]},$$

which is a free parameter related to the parameter $a$ in equation (1). We adopt $\alpha_{\text{ox}} = -1.4$. The observational values of these parameters for NGC 4051 are summarized in Table 5.

The calculations for IB clouds are continued until the electron temperature drops below 3000 K, since gas with a temperature lower than 3000 K is not thought to contribute significantly to the emission lines. The calculations for MB clouds are done until the column density of the MB clouds reaches a value given as a free parameter.

4.2. Results

First, we discuss the physical conditions of the IB clouds. Assuming that the low-ionization forbidden lines are radi-
the hydrogen column density of MB clouds $N_{MB} > 10^{21}$ cm$^{-2}$, [O III] $\lambda 5007$ also begins to radiate from the MB clouds (see Fig. 9). Therefore, we examine two cases, $N_{MB} = 10^{20.5}$ and $10^{21.0}$ cm$^{-2}$. Assuming the size of the HINER to be $D_{HINER} = 150$ pc $= 4.63 \times 10^{14}$ cm, we obtain $n_{MB} \approx 10^{-0.17}$ cm$^{-3}$ for $N_{MB} = 10^{20.5}$ cm$^{-2}$ and $n_{MB} \approx 10^{0.33}$ cm$^{-3}$ for $N_{MB} = 10^{21}$ cm$^{-2}$, because $n_{MB} \approx N_{MB}/D_{HINER}$. Since the former density is too low to produce sufficiently strong emission, we adopt the latter case, that is, $n_{MB} = 10^{0.33}$ cm$^{-3}$ and $N_{MB} = 10^{21}$ cm$^{-2}$. In Table 6, we give the emission-line fluxes normalized by H$\beta$ (narrow component) for the IB and MB clouds described above.

It seems reasonable that the nuclear emission-line region of NGC 4051 is a mixture of both IB and MB clouds. To reproduce the observed [Fe x]/H$\beta$ ratio, we find that the relative contribution of the MB clouds is 5.3% in the H$\beta$ luminosity. We compare the total calculated line ratios with the observed values in Table 7. We find that [O III], [N II], and [S II] are 2 or 3 times stronger than the observational values although high-ionization lines are consistent with the observation. This discrepancy can be reconciled if there is another emission component that radiates hydro-

**TABLE 5**

| Parameter | Observational Value | Adopted Value |
|-----------|---------------------|---------------|
| $T_{MB}$  | ...                 | $1.5 \times 10^5$ |
| $x_{MB}$  | $-1.88 \pm 0.18^a$ (ROSAT) | $-0.5^a$ |
| $x_{X}$   | $-0.66^b$ (Ginga) | $-1.0$ |
| $x_{X}$   | $-0.85 \pm 0.07^c$ (ASCAY) | $-1.30^d$ (ROSAT) |
| $x_{MB}$  | $-1.32^d$ (ROSAT) | $-1.4^d$ |

$^a$ A recommended value in CLOUDY (see Ferland and Francis 1993).
$^b$ Walter et al. 1994.
$^c$ Guainazzi et al. 1996.
$^d$ Komossa & Fink 1997.
$^e$ A recommended value in CLOUDY (see Ferland and Zamorani et al. 1981).

**TABLE 6**

| Line         | Observed* | IB Clouds | MB Clouds |
|--------------|-----------|-----------|-----------|
| H$\beta$/N  | $\lambda 4861$ | 1.000     | 1.000     | 1.000     |
| [O III] $\lambda 5007$ | 1.294     | 3.937     | 0.114     |
| [Fe xiv] $\lambda 5303$ | $<0.063$   | 0.000     | 0.160     |
| He I $\lambda 5876$ | 0.130     | 0.141     | 0.001     |
| [Fe vi] $\lambda 6087$ | $<0.060$   | 0.000     | 0.014     |
| [O I] $\lambda 6300$ | 0.113     | 0.091     | 0.000     |
| [Fe x] $\lambda 6374$ | 0.136     | 0.000     | 2.658     |
| H$\alpha$/N 5656 | 3.030     | 2.901     | 2.706     |
| [N II] $\lambda 6584$ | 0.838     | 2.200     | 0.000     |
| [S II] $\lambda 6716$ | 0.127     | 0.405     | 0.000     |
| [S II] $\lambda 6731$ | 0.136     | 0.441     | 0.000     |
| [Fe xi] $\lambda 7282$ | ...       | 0.000     | 1.784     |

* The reddening-corrected relative intensities. $I$(H$\beta$/N) = $7.406 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$.

**Fig. 8.** Determination of the parameters for ionization-bounded clouds. The straight lines show the observed reddening-corrected line ratios, and the curves show the calculated line ratio for various parameters (here, hydrogen density and ionization parameter). The small circles are located at the crossover for the lines describing the observed and calculated line ratios; therefore, the circles indicate the estimated parameters.
gen recombination lines mainly. Hereafter we call this the "contamination component." Possible contamination sources are either broad-line regions (BLRs), nuclear star-forming regions, or both (§ 5). Note that this contamination component must not destroy the line ratios such as \([\text{S} \, \text{II}] \, \lambda 6717, 6731/[\text{O} \, \text{III}] \, \lambda 5007, [\text{S} \, \text{II}] \, \lambda 6716/\lambda 6731,\) and so on.

Flux contributions of the IB clouds, the MB clouds, and the contamination component of Balmer lines are treated as free parameters \(a\) and \(b;\) \(a\) is the \(\text{H} \beta\) flux ratio between the MB clouds and the IB clouds, and \(b\) is that between the contamination component and the IB clouds. We can find a probable set of the line ratios that is consistent with the observation. Here we assume a ratio of \(\text{H} \alpha/\text{H} \beta\) for the contamination component of 3.1. Because \([\text{Fe} \, \text{II}]\) is assumed to emit from the MB clouds, we obtain a relation,

\[
\frac{[\text{Fe} \, \text{II}]}{\text{H} \beta}_{\text{obs}} = \frac{a[\text{Fe} \, \text{II}]/\text{H} \beta_{\text{MB}}}{1 + a + b}.
\]

Since we can regard \([\text{O} \, \text{III}] \, \lambda 5007\) as a representative low-ionization emission line, we obtain another relation,

\[
\frac{[\text{O} \, \text{III}]}{\text{H} \beta}_{\text{obs}} = \frac{[\text{O} \, \text{III}]/\text{H} \beta_{\text{IB}}}{1 + a + b}.
\]

In Table 6, we give \(([\text{Fe} \, \text{II}]/\text{H} \beta)_{\text{obs}}, ([\text{Fe} \, \text{II}]/\text{H} \beta_{\text{MB}}), ([\text{O} \, \text{III}]/\text{H} \beta)_{\text{obs}},\) and \(([\text{O} \, \text{III}]/\text{H} \beta_{\text{IB}}),\) Using these relations, we find \(a = 0.161\) and \(b = 1.868.\) These results mean that the contributions of the IB clouds, the MB clouds, and the contamination component are 33.0\%, 5.3\%, and 61.7\% in the \(\text{H} \beta\) luminosity, respectively. We give a summary of the set of the line ratios in Table 8. Although we do not observe \([\text{Fe} \, \text{II}] \, \lambda 7892,\) previous observations (Penston et

![Diagram](Image)

**Fig. 9.**—Determination of the parameters for matter-bounded clouds. The curves show the calculated fluxes normalized by \(\text{H} \beta\) for the varying hydrogen column density in the case of \(\log \, U = -0.6, -0.5,\) and \(-0.4\) (left to right).

### Table 7

**Comparison of Calculated Line Ratios of IB + MB Model with Observed Values**

| Line       | IB Clouds | MB Clouds | Total  | Observed a |
|------------|-----------|-----------|--------|------------|
| H\(\beta/N\) \(\lambda 4861\). . . . . . . . | 0.947 | 0.053 | 1.000 | 1.000 |
| [O \, III] \(\lambda 5007\) . . . . . | 3.728 | 0.006 | 3.734 | 1.294 |
| [Fe \, xiv] \(\lambda 5303\) . . . . . | 0.000 | 0.008 | 0.008 | <0.0063 |
| He \(\lambda 5876\) . . . . . | 0.134 | 0.000 | 0.134 | 0.130 |
| [Fe \, vii] \(\lambda 6087\) . . . . . | 0.000 | 0.001 | 0.001 | <0.0060 |
| [O \, iii] \(\lambda 6300\) . . . . . | 0.086 | 0.000 | 0.086 | 0.113 |
| [Fe \, x] \(\lambda 6374\) . . . . . | 0.000 | 0.141 | 0.141 | 0.136 |
| Hz\(\beta/) \(\lambda 6563\) . . . . . | 2.747 | 0.143 | 2.890 | 3.030 |
| [N \, ii] \(\lambda 6584\) . . . . . | 2.083 | 0.000 | 2.083 | 0.838 |
| [S \, ii] \(\lambda 6716\) . . . . . | 0.384 | 0.000 | 0.384 | 0.127 |
| [S \, ii] \(\lambda 6731\) . . . . . | 0.418 | 0.000 | 0.418 | 0.136 |
| [Fe \, xi] \(\lambda 7892\) . . . . . | 0.000 | 0.095 | 0.095 | ... |

- **Normalized by observed \(H\beta_{\text{narrow}}\).**
- **The reddening-corrected relative intensities \(I(\text{H} \beta/\text{N}) = 7.406 \times 10^{-13} \text{ergs s}^{-1} \text{cm}^{-2}\).**

### Table 8

**Comparison of Calculated Line Ratios of Contaminated Model with Observed Values**

| Line       | IB Clouds | MB Clouds | Contamination b | Total  | Observed a |
|------------|-----------|-----------|-----------------|--------|------------|
| H\(\beta/N\) \(\lambda 4861\). . . . . . . . | 0.330 | 0.053 | 0.610 | 1.000 | 1.000 |
| [O \, iii] \(\lambda 5007\) . . . . . | 1.299 | 0.006 | 1.305 | 1.294 |
| [Fe \, xiv] \(\lambda 5303\) . . . . . | 0.000 | 0.008 | 0.000 | 0.008 | <0.0063 |
| He \(\lambda 5876\) . . . . . | 0.000 | 0.000 | 0.000 | 0.000 | <0.060 |
| [Fe \, vii] \(\lambda 6087\) . . . . . | 0.000 | 0.001 | 0.000 | 0.001 | <0.060 |
| [O \, iii] \(\lambda 6563\) . . . . . | 0.000 | 0.141 | 0.000 | 0.141 | 0.136 |
| Hz\(\beta/) \(\lambda 6584\) . . . . . | 0.960 | 0.143 | 1.000 | 1.868 |
| [N \, ii] \(\lambda 6584\) . . . . . | 0.726 | 0.000 | 0.726 | 0.838 |
| [S \, ii] \(\lambda 6716\) . . . . . | 0.134 | 0.000 | 0.134 | 0.127 |
| [S \, ii] \(\lambda 6731\) . . . . . | 0.146 | 0.000 | 0.146 | 0.136 |
| [Fe \, xi] \(\lambda 7892\) . . . . . | 0.000 | 0.095 | 0.000 | 0.095 | ... |

- **Normalized by observed \(H\beta_{\text{narrow}}\).**
- **We assume the ratio of \(H\alpha/\text{H} \beta\) for this contamination component to be 3.1.**
- **The reddening-corrected relative intensities \(I(\text{H} \beta/\text{N}) = 7.406 \times 10^{-13} \text{ergs s}^{-1} \text{cm}^{-2}\).**
al. 1984; Erkens et al. 1997) show [Fe x] λ7892/[Fe x] λ6374 = 0.324 or 0.514. Our calculated [Fe x] λ7892/[Fe x] λ6374 is 0.674, and this is not so different from previous observations. On the other hand, the observed [O I] λ6300 is 4 times stronger than the model value. One reason for this may be that [O I] arises partly from other regions that we do not take into account in our model.

Finally, in Table 9, we give a summary of the three emission components adopted for the nuclear emission-line region of NGC 4051. These parameters are determined uniquely in the process described above. However, there may be other models that explain the observed line ratios of NGC 4051. Recently, Contini & Viegas (1999) proposed a multicolor model in which the existence of shocks is introduced for NGC 4051. Their model explains the optical line ratios and the continuum spectral energy distribution, although they did not mention the spatial extension of ionized regions. To discriminate which model is more plausible, further detailed observations will be necessary.

5. DISCUSSION

As we have shown in previous sections, the observed emission-line ratios of the nuclear region of NGC 4051 are consistently understood by introducing three emission components, (1) the ionization-bounded clouds, (2) matter-bounded clouds, and (3) the contamination component, to the Balmer emission lines. Although our three-component model appears to be consistent with the observations, our result implies that the majority of Balmer emission (~60%) arises from the contamination component. Now we consider the problem, what is the contamination component?

First, we consider this problem for the nuclear region. Possible candidates for the contamination components are either the BLR, nuclear star-forming regions, or both. If NGC 4051 belongs to a class of NLS1’s (Boller et al. 1996; Komossa & Fink 1997), it seems hard to measure the contribution from the BLR to the Hβ emission because of the narrow width of the broad line, if present. It is also possible to consider that NGC 4051 experiences a burst of massive star formation in its nuclear region, because there is a great deal of cold molecular gas, as well as circumnuclear star-forming regions (Kohno 1997; Vila-Vilaró, Taniguchi, & Nakai 1998). Peterson, Crenshaw, & Meyers (1985) reported that the Hβ of NGC 4051 exhibits time variability (enhanced by 85% in Hβ flux) on timescales shorter than ~2 yr, that is, the Hβ of NGC 4051 more or less contains the broad component. Although we have no way to evaluate the contribution of this BLR contamination to the total flux quantitatively, it is possible that all of the contamination component is contributed from the BLR. In addition, the nuclear star formation may contribute to the contamination. Kohno (1997) discussed the gravitational instability of the nuclear molecular gas of some Seyfert galaxies using Toomre’s Q-value. The Toomre Q-parameter characterizes the criterion for local stability in thin isothermal disks and is expressed as $Q = \Sigma_{\text{crit}}/\Sigma_{\text{gas}}$, where $\Sigma_{\text{crit}}$ is the critical surface density. He gave $Q = 0.90$ for the nuclear region of NGC 4051. This means that the molecular gas in the nuclear region of NGC 4051 is thought to be gravitationally unstable.

In any case, about 60% of observed Hβ is not originated from the NLR in the nuclear region of NGC 4051. This means that the line ratios of the nuclear region suffer seriously from contamination. In Figure 10, we replot the excitation diagnostic diagram using the line ratios, from which the contamination component is subtracted. This diagram shows that the contamination-subtracted line ratios of the nuclear region show the typical AGN-like excitation condition. Therefore, we conclude that the unusual excitation condition is due to the contamination component. High spatial resolution optical spectroscopy or X-ray imaging observations will be helpful in investigating whether or not the star formation activity dominates the flux of Hβ.

Second, we consider the off-nuclear regions. As shown in Figure 7, the three off-nuclear regions (west, southwest, and southeast) also show H β region-like excitations. Since a typical size of the BLR is ~0.01 pc (e.g., Peterson 1997), it is likely that these excitation conditions are due to circumnuclear star-forming regions.

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![FIG. 10.—Diagnostic diagram, same as in Fig. 6. The filled circle shows the excitation condition of the nuclear region corrected for the contamination effect.](image-url)
REFERENCES

Adams, T. F. 1977, ApJS, 33, 19
Anderson, K. S. 1970, ApJ, 162, 743
Antonucci, R. R. J. 1993, ARA&A, 31, 473
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Binette, L. 1985, A&A, 143, 334
Binette, L., Wilson, A. S., Raga, A., & Storchi-Bergmann, T. 1997, A&A, 327, 909
Binette, L., Wilson, A. S., & Storchi-Bergmann, T. 1996, A&A, 312, 365
Boller, T., Brandt, W. N., & Fink, H. 1996, A&A, 305, 53
Contini, M., & Viegas, S. M. 1999, ApJ, 523, 114
De Robertis, M. M., & Osterbrock, D. E. 1986, ApJ, 301, 727
Erkens, U., Appenzeller, I., & Wagner, S. 1997, A&A, 323, 707
Ferguson, J. W., Korista, K. T., Baldwin, J. A., & Ferland, G. J. 1997a, ApJ, 487, 122
Ferguson, J. W., Korista, K. T., & Ferland, G. J. 1997b, ApJS, 110, 287
Ferland, G. J. 1996, Hazy: A Brief Introduction to Cloudy (Lexington: Univ. Kentucky Dept. Phys. Astron.)
Ferland, G. J., & Netzer, H. 1983, ApJ, 264, 105
Ferland, G. J., & Osterbrock, D. E. 1986, ApJ, 300, 658
Francis, P. J. 1993, ApJ, 407, 519
Grandy, S. A. 1978, ApJ, 221, 501
Golev, V., Yankulova, I., Bonev, T., & Jockers, K. 1995, MNRS, 273, 129
Guainazzi, M., Mihara, T., Otani, C., & Matsuoka, M. 1996, PASJ, 48, 781
Halpern, J. P., & Steiner, J. E. 1983, ApJ, 269, L37
Kohno, K. 1997, Ph.D. thesis, Tokyo Univ.
Komossa, S., & Fink, H. 1997, A&A, 322, 719
Korista, K. T., & Ferland, G. J. 1989, ApJ, 343, 678
Kosugi, G., et al. 1995, PASP, 107, 474
Murayama, T., & Taniguchi, Y. 1998a, ApJ, 497, L9 (MT98a)
—. 1998b, ApJ, 503, L115 (MT98b)
Murayama, T., Taniguchi, Y., & Iwasawa, K. 1998, AJ, 115, 460 (MT98)
Nussbaumer, H., & Osterbrock, D. E. 1970, ApJ, 161, 811
Oke, J. B., & Sargent, W. L. W. 1968, AJ, 73, 895
Osterbrock, D. E. 1969, Astrophys. Lett., 4, 57
—. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, CA: Univ. Sci.)
Osterbrock, D. E., & Dahari, O. 1983, ApJ, 273, 478
Osterbrock, D. E., & Pogge, R. W. 1985, ApJ, 297, 166
Penston, M. V., Fosbury, R. A. E., Boksenberg, A., Ward, M. J., & Wilson, A. S. 1984, MNRS, 208, 347
Peterson, B. M. 1997, An Introduction to Active Galactic Nuclei (Cambridge: Cambridge Univ. Press)
Peterson, B. M., Crenshaw, D. M., & Meyers, K. A. 1985, ApJ, 298, 283
Phillips, A. P., Gondhalekar, P. M., & Pettini, M. 1992, MNRS, 200, 687
Pier, E. A., & Voit, G. M. 1995, ApJ, 450, 628
Seyfert, C. K. 1943, ApJ, 97, 28
Stasinska, G. 1984, A&A, 135, 341
Storchi-Bergmann, T. 1991, MNRS, 249, 404
Storchi-Bergmann, T., & Pastoriza, M. G. 1990, PASP, 102, 1359
Storchi-Bergmann, T., Schmitt, H. R., Calzetti, D., & Kinney, A. L. 1998, AJ, 115, 909
Ulvestad, J. S., & Wilson, A. S. 1984, ApJ, 285, 439
Veilleux, S. 1988, AJ, 95, 1695
Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295
Viegas-Aldrovandi, S. M. 1988, ApJ, 330, L9
Viegas-Aldrovandi, S. M., & Contini, M. 1989, A&A, 215, 253
Viegas-Aldrovandi, S. M., & Gruenwald, R. B. 1988, ApJ, 324, 683
Vila-Vilaro, B., Taniguchi, Y., & Nakai, N. 1998, AJ, 116, 1553
Walter, R., Orr, A., Courvoisier, T. J.-L., Fink, H. H., Makino, F., Otani, C., & Wamsteker, W. 1994, A&A, 285, 119
Wilson, A. S., Binette, L., & Storchi-Bergmann, T. 1997, ApJ, 482, L131
Yee, H. K. C. 1980, ApJ, 241, 894
Zamorani, G., et al. 1981, ApJ, 245, 357