PHYSICAL CONDITIONS IN THE INNER NARROW-LINE REGION OF THE SEYFERT 2 GALAXY NGC 1068

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ABSTRACT

The physical conditions in the inner narrow-line region (NLR) of the Seyfert 2 galaxy NGC 1068 are examined using ultraviolet and optical spectra and photoionization models. The spectra are Hubble Space Telescope archive data obtained with the Faint Object Spectrograph (FOS). We selected spectra of four regions, taken through the 0.3 FOS aperture covering the full FOS 1200–6800 Å wave band. Each region is approximately 20 pc in extent, and all are within 100 pc of the apparent nucleus of NGC 1068. The spectra show similar emission-line ratios from a wide range of ionization states for the most abundant elements. After extensive photoionization modeling, we interpret this result as an indication that each region includes a range of gas densities, which we included in the models as separate components. Supersolar abundances were required for several elements to fit the observed emission-line ratios. Dust was included in the models, but apparently dust-to-gas fraction varies within these regions. The low-ionization lines in these spectra can be best explained as arising in gas that is partially shielded from the ionizing continuum. Although the predicted line ratios from the photoionization models provide a good fit to the observed ratios, it is apparent that the model predictions of electron temperatures in the ionized gas are too low. We interpret this as an indication of additional collisional heating due to shocks and/or energetic particles associated with the radio jet that traverses the NLR of NGC 1068. The density structure within each region may also be the result of compression by the jet.

Subject headings: galaxies: individual (NGC 1068) — galaxies: Seyfert — ultraviolet: galaxies

1. INTRODUCTION

NGC 1068, one of the initial set of emission-line galaxies studied by Seyfert (1943), is the nearest (z = 0.0036) and the best studied of the Seyfert 2 galaxies. NGC 1068 has been observed extensively in all wave bands from the radio to the X-ray. Not only is there evidence of ionizing radiation from the central AGN, but a prominent radio jet exists in the narrow-line region (NLR) (Wilson & Ulvestad 1983), and there is a starburst ring approximately 1 kpc from the nucleus (Snijders, Briggs, & Boksenberg 1982; Bruhweiler, Troung, & Altner 1991). The detection of polarized optical continuum and broad permitted lines (Miller & Antonucci 1983; Antonucci & Miller 1985) in the nucleus of NGC 1068 was the inspiration for the “unified model” for Seyfert galaxies, in which the differences between types 1 and 2 were attributed to viewing angle (Antonucci 1994), with Seyfert 2 galaxies characterized by obscuration of their central engines.

Because of its relative proximity, NGC 1068 offers a unique opportunity to study the detailed physics of the NLR gas. Studies of the conditions in the NLR can provide a check on the estimates of the luminosity and spectral characteristics of the intrinsic ionizing continuum proposed by Pier et al. (1994) and Miller, Goodrich, & Mathews (1991). Ground-based observations and analysis of the extended NLR (Balick & Heckman 1985; Evans & Dopita 1986; Bergeron, Petitjean, & Durret 1989) have shown that gas at large distances from the nucleus (~ kiloparsecs) is likely to be photoionized by the radiation from the central active galactic nucleus (AGN). It follows that photoionization must be an important if not dominant process in the inner NLR of NGC 1068 as well. Before the Hubble Space Telescope (HST), it was difficult to examine the conditions in the inner 100 pc. Ground-based optical spectra (see, e.g., Koski 1978) and UV spectra from IUE (Snijders et al. 1982) that sampled large areas (~3") within NGC 1068 did not have the resolution to provide the necessary constraints on models of the emission-line gas. With HST resolution and spectral coverage, we now have access to spatially resolved spectra of the inner NLR.

Although it is clear that the NLR gas is photoionized (Netzer 1997), it is possible that collisional processes are important as well (Kris et al. 1992). Detailed photoionization models can help distinguish between the contributions of various possible sources of ionization and heating in the NLR. A better determination of the relative contributions of such processes may lead to an understanding of the physical nature of the NLR, and possibly its origin and evolution. Even though the ionizing continuum in NGC 1068 cannot be directly observed, the relative radial distances and physical extents of the regions observed are known, which provides important new constraints on the models.

2. OBSERVATIONS AND ANALYSIS

There are a large number of FOS observations of NGC 1068 in the HST archives. FOS spectra of the brightest point in the visible region were obtained, which we refer to as the “nucleus”; some of the spectra have been published by Caganoff et al. (1991) and Antonucci, Hurt, & Miller (1994). Spectra were also obtained at various offset positions from the nucleus, but they have not been published. In
the HST archives, these positions are often referred to as “clouds” (e.g., cloud 1), but we will refer to them as “positions” (e.g., position 1), since FOC and WFPC2 [O III] images show that even the FOS 0.3 aperture encompasses a number of emission-line knots. We chose to limit the number of spectra for this study to satisfy several criteria. First, the position observed must have full wavelength coverage from 1200 to 6800 Å at good resolution (Δλ/Δλ ≈ 1000) to provide a full range of emission-line diagnostics; thus only pointings that include observations with the G130H, G190H, G270H, G400H, and G570H gratings were used. Second, we wanted to concentrate on regions of small spatial extent to minimize the range in physical conditions, so only observations through the 0.3 aperture were included. Finally, for observations obtained of the same region at different times, the acquisition techniques had to be the same, and we required that the spectra match well where they overlap. Table 1 gives a summary of the observations that we used. Note that observations of NGC 1068 and NGC 1068-NUC are of the same region (the nucleus).

Our requirements resulted in UV and optical spectra of the nucleus and three offset positions in the inner NLR through a 0.3 aperture. The nucleus was acquired by peakups through successively smaller apertures (1.0, 0.5, and 0.3) using light from the G270H grating. Spectra of the other positions were obtained by offsetting to positions of bright emission seen in the original WFPC2 narrowband images (centered on various emission lines such as [O III]). Peakups and spectra were obtained with the FOS/BLUE detector and G130H and G190H gratings, and with the FOS/RED detector and G270H, G400H, and G570H gratings. In addition, blue G270H spectra were obtained through successively smaller apertures (1.0, 0.5, and 0.3) using light from the G270H grating. Spectra of the nucleus after peakups with the blue detector. In this case, after scaling the red G270H spectrum by a factor of 1.1, the features in both blue and red G270H spectra are essentially identical. Thus, we are confident that peakups on the nucleus performed at different times and with different detectors resulted in observations of the same region. Since the offsets are highly accurate, and the spectra at each offset position matched to within 10% in the wavelength regions of overlap, we are confident of these pointings as well. To account for the small (≤10%) absolute flux differences, all of the spectra from a given position were scaled to match the flux level of the red G270H spectra.

Figure 1 shows the locations of the aperture for these pointings, superimposed on an FOC [O III] λ5007 profile obtained from the HST archives and the axis of the radio jet (Gallimore et al. 1996). We note that the FOS observations were obtained prior to the installation of COSTAR on HST in 1993 December, so a substantial amount of light from outside the projected aperture is included in each of these spectra. These effects are discussed in greater detail below. At the distance of NGC 1068, 0.3 corresponds to 21 pc (for z = 0.0036 and H₀ = 75 km s⁻¹ Mpc⁻¹).

Figures 2, 3, and 4 show the far-UV, near-UV, and optical spectra for each position. We note that the N v λ1239 and 1243 and C iv λ1548 and 1551 doublets, normally blended together in Seyfert 2 spectra, are resolved in some of the far-UV spectra, since we are isolating specific kinematic regions and these lines are therefore relatively narrow. The blue component of the doublet appears to be smaller than the red component in each case, because Galactic and intrinsic absorption features (probably from the halo of NGC 1068) are absorbing the blue side of the doublet emission in each case. We also note that the spectra from different positions are very similar in appearance, given the differences in absolute fluxes, and that the N v and [Ne v] λλ3346 and 3426 lines are unusually strong in each spectrum. We will explore these issues later in the paper.

We measured the fluxes of most of the narrow emission lines by direct integration over a local baseline determined by linear interpolation between adjacent continuum regions. For severely blended lines such as Hα and [N ii] λλ6548 and 6584, we used the [O iii] λ5007 profile as a

| Archive Name | Data Set Name | Detector | Grating | Exposure (s) | Observation Date |
|---------------|---------------|----------|---------|-------------|------------------|
| NGC 1068, NUC… | Y0GQ010T | FOS/BL | G130H | 1500 | 1991 Jan 27 |
| NGC 1068 | Y0GQ0105T | FOS/BL | G190H | 1000 | 1991 Jan 27 |
| NGC 1068 | Y0GQ0107T | FOS/BL | G270H | 700 | 1991 Jan 27 |
| NGC 1068 | Y0GQ0106T | FOS/BL | G130H | 1500 | 1991 Jan 25 |
| NGC 1068, Cloud 1 | Y0GQ0109T | FOS/BL | G190H | 1000 | 1991 Jan 25 |
| NGC 1068, Cloud 2 | Y0GQ0108T | FOS/BL | G270H | 700 | 1991 Jan 25 |
| NGC 1068, Cloud 3 | Y0GQ0107T | FOS/BL | G570H | 600 | 1991 Jan 25 |
| NGC 1068, Cloud 1 | Y0GQ0106T | FOS/BL | G190H | 1000 | 1991 Jan 25 |
| NGC 1068, Cloud 2 | Y0GQ0109T | FOS/BL | G270H | 700 | 1991 Jan 25 |
| NGC 1068, Cloud 3 | Y0GQ0108T | FOS/BL | G570H | 600 | 1991 Jan 25 |
| NGC 1068, Cloud 1 | Y0GQ0107T | FOS/BL | G190H | 1000 | 1991 Jan 25 |
| NGC 1068, Cloud 2 | Y0GQ0106T | FOS/BL | G270H | 700 | 1991 Jan 25 |
| NGC 1068, Cloud 3 | Y0GQ0109T | FOS/BL | G570H | 600 | 1991 Jan 25 |
| NGC 1068, Cloud 1 | Y0GQ0107T | FOS/BL | G190H | 1000 | 1991 Jan 25 |
| NGC 1068, Cloud 2 | Y0GQ0106T | FOS/BL | G270H | 700 | 1991 Jan 25 |
| NGC 1068, Cloud 3 | Y0GQ0109T | FOS/BL | G570H | 600 | 1991 Jan 25 |

* 0.3 diameter aperture.
Fig. 1.—FOC [O iii] image of NGC 1068 with the four FOS aperture positions. The square pattern of spots with low counts are instrumental reseau marks. North is up and east is to the left. The apertures are 0.3 in diameter. The dotted line traces the axis of the radio jet.

Fig. 2.—FOS far-UV (G130H) spectra of NGC 1068 for the nucleus (N) and positions 1, 2, and 3.

Fig. 3.—FOS near-UV (G190H, G270H) spectra of NGC 1068 for the nucleus (N) and positions 1, 2, and 3.
template to deblend the lines (see Crenshaw & Peterson 1986). We then determined the reddening of the narrow emission lines from the observed $\text{He}^\text{II}$ $\lambda 1640/\lambda 4686$ ratio, the Galactic reddening curve of Savage & Mathis (1979), and an intrinsic $\text{He}^\text{II}$ ratio of 7.2, which is expected from recombination (Seaton 1978) at the temperatures and densities typical of the NLR (see also § 3). We determined errors in the dereddened ratios from the sum in quadrature of the errors from three sources: photon noise, different reasonable continuum placements, and reddening.

Table 2 gives the dereddened narrow-line ratios, relative to $\text{H}^\text{II}$, and errors in the dereddened ratios for each position. Inspection of this table shows that the emission-line ratios from the different regions are indeed very similar. At the end of the table, we give the $\text{H}^\text{II}$ fluxes (ergs s$^{-1}$ cm$^{-2}$) in the aperture and the reddening values that we determined from the $\text{He}^\text{II}$ ratios.

As we mentioned earlier, these observations were obtained prior to the installation of COSTAR. Hence, the presence of broad wings on the point-spread function at the aperture plane leads to substantial contamination of the observed flux by emission-line knots outside of the projected aperture. To estimate this effect on the observed spectra, we retrieved (from the STScI) a model pre-COSTAR point-spread function (PSF) for the FOS red detector at 5000 Å, which was generated and described by Evans (1993). We interpolated over the reseaux in the post-COSTAR FOC [O III] image in Figure 1 (which has a spatial resolution of 0.014 pixel$^{-1}$), extracted subimages through apertures of different sizes, and convolved the original image and subimages with the FOS PSF image. We then determined the percentage of the [O III] flux in the spectrum of each region that is contributed by emission within the projected 0.3 aperture, within a concentric aperture of diameter 0.6, and from the remainder of the NLR flux in the FOC image. These values are respectively 61%, 22%, and 17% for the nucleus; 53%, 30%, and 17% for position 1; 54%, 25%, and 21% for position 2; and 65%, 20%, and 15% for position 3. Thus, in these cases, we are sampling regions considerably larger than the projected aperture sizes; however, in each pointing, at least $\sim$80% of the [O III] flux is coming from within $\sim$0.6 of the aperture centers. Position 1 is $\sim$0:2 from the nucleus, so we are primarily sampling the same region in this case. For positions 2 and 3, we are sampling regions that are relatively distinct, since they are 0.6 and 1.5 from the nucleus.

3. PHOTOIONIZATION MODELS

As in our previous studies (see, e.g., Kraemer et al. 1998), we have taken a simple approach in setting the initial input values for photoionization models. In previous cases where we could not resolve the emission-line region, we could effectively adjust the distance of the emission-line gas from the source of the ionizing radiation to obtain a good match with the observations. With the current data set we have spectra from spatially resolved regions, and, therefore, the distance of the gas from the ionizing source is more tightly constrained. In turn, we can be more flexible in adjusting input parameters such as abundances and optical thickness if our initial parameters are not sufficient. Such an approach can produce a better fit to the observed line ratios, but it is important to bear in mind that it still may not result in a unique solution for the set of physical conditions in the emission-line region. We will return to this point in the following section.

The photoionization code used for this study has been described in detail in our previous papers (see, e.g., Kraemer et al. 1998), and we will not repeat the description here. A few points should be mentioned, however. First, it is important to bear in mind that this code assumes a slab geometry, with photon escape out of the illuminated face. The effects of dust are included, as well as internal reddening, trapping of UV resonance lines, and screening of the ionization radiation. Forward scattering by the grains is assumed. For a full explanation of the treatment of dust in this code, see Kraemer (1985). As per the standard convention, models are parameterized in terms of the density of atomic hydrogen ($N_{\text{H}}$) and the dimensionless ionization parameter at the illuminated face of the cloud:

$$U = \int_{v_0}^{\infty} \frac{L_e}{h\nu} \frac{dv}{4\pi D^2 N_{\text{H}}} c,$$

where $L_e$ is the frequency-dependent luminosity of the ionizing continuum, $D$ is the distance between the cloud and the ionizing source, and $h\nu_0 = 13.6$ eV.

4. CHOOSING THE MODEL INPUT PARAMETERS

In spite of the pre-COSTAR PSF problems described in § 2, we know that the majority of the line emission seen in these spectra arise in or near the projected aperture locations shown in Figure 1. The spectra from each of these regions show a wide range of ionization states for the most abundant elements, indicating gas with a range of physical conditions within each region. In simple multicomponent models of an entire NLR (see Kraemer et al. 1994), one can include contributions from gas in various ionization states by placing the components at different distances from the ionizing source. This means that there can be a large amount of low-ionization, low-density gas at large radial distances; having a large volume of this gas can balance the fact that such components have low emissivity relative to higher ionization, denser material close to the ionizing source, as long as the covering factor of the inner component is small. We do not have this flexibility in modeling these spectra. If the line emission is from photoionized gas,
there must be a range in density within the observed regions. After running an initial set of simple multi-component models, it became clear that we needed additional parameters to match the observations. These parameters include elemental abundances, “shielding” of one of our components, optical depth, and dust.

Although previous photoionization studies have suggested that the elemental abundances in the NLR may be non-solar (Osterbrock 1989), line ratios indicative of non-solar abundances can often be explained by including multi-component models of varying density. For these data, however, there are clear indications of non-solar abundances. For example, as discussed by Netzer (1997), the ratio of the O III 1501 and Hβ lines can be used to estimate the ratio of elemental oxygen to nitrogen, since their ionization regions tend to show large overlap. The theoretical ratio is as follows:

$$\frac{I(\lambda 1664)}{I(\lambda 1750)} = 0.41 T_4^{-0.04} \exp \left( -0.43 \frac{T_4}{T_a} \right) \frac{N(O^+)}{N(N^+)}$$

where $T_a$ is the temperature in units of 10,000 K. The average intensity ratio from the four regions sampled is 0.65. If we assume $T = 15,000$ K, $N(O)/N(N) \sim 2.1$, which is 0.36 times solar. Netzer interprets this as a large oxygen underabundance and offers the observed O III 1501/Hβ ratio as further evidence, since it yields $N(O)/N(N) \sim 0.73$. Averaging over the four regions, we obtain $N(O)/N(N) \sim 1.8$, which is approximately solar. Therefore, it is likely that we are seeing enhanced nitrogen rather than depleted oxygen.

Another indication that the nitrogen is supersolar is the ratio of the N v λ1240 line to the He II λ1640. In photoion-
ized gas, the N v/He II ratio is typically less than unity (Ferland et al. 1996). Although this ratio can increase if the gas is so optically thin that the edge of the He II Strömgren zone is never attained, in such cases the O v λ1216 and O vi λ1035 lines become inordinately strong. (Netzer was able to achieve such ratios without excess O v and O vi emission by depleting the oxygen by a factor of 3, which we do not think is supported by the observations.) Ferland et al. (1996) suggest that relative enhancement of nitrogen can better explain such line ratios. Although their study was of the spectra of luminous QSOs, not only are the same physical processes at work in the ionized gas, but it is not too surprising that there may be heavily reprocessed material in the nucleus of a Seyfert galaxy since it is possible that the AGN phenomenon was proceeded by a massive nuclear starburst (see, e.g., Osterbrock 1993). Finally, the [N ii] λλ6548 and 6584 lines are quite strong in these spectra (4–5 times the strength of Hβ) while the [O ii] λ3727 line is weak. Although this is possibly because of collisional suppression of the [O ii] line, it is also plausible that we are seeing the effect of an overabundance of nitrogen. This will be explained in more detail in the discussion of the model results. For the models, we assume a 3 times solar nitrogen abundance.

The lines of Ne +3, Ne +4, and Fe +6 are quite strong in all of these spectra. Fitting the coronal lines with solar abundances is often a problem for photoionization models (Kraemer et al. 1998), but as Oliva (1997) suggests, they can be enhanced if these elements are overabundant. Furthermore, from their analysis of ASCA data, Netzer & Turner (1997) postulate that the Fe/O ratio is quite high in the X-ray-emitting gas in NGC 1068. For these models, we have assumed that both iron and neon are supersolar by a factor of 2 in abundance.

Although it is possible that other elements may be overabundant, there is no indication from the spectra that this is the case. Therefore, we have chosen to keep them at solar abundances. The numerical abundances, relative to hydrogen, assumed for these models are as follows: He = 0.1, C = 3.4 × 10⁻⁴, O = 6.8 × 10⁻⁴, N = 3.6 × 10⁻⁴, Ne = 2.2 × 10⁻⁴, S = 1.5 × 10⁻³, Si = 3.1 × 10⁻⁵, Mg = 3.3 × 10⁻⁵, and Fe = 8.0 × 10⁻⁵.

We have assumed in these simple models that the gas is photoionized by radiation from the central AGN. In NGC 1068, as in most Seyfert 2 galaxies, it is impossible to measure the intrinsic ionizing continuum directly, since the inner regions of these objects are usually obscured by a large column of dusty gas. The ionizing continuum is only observed by light scattered into our line of sight by a scattering medium, which possibly consists of free electrons (see Antonucci 1994 for the details of this basic model). There have been attempts (Miller et al. 1991; Pier et al. 1994) to determine the intrinsic luminosity and spectral energy distribution (SED) of NGC 1068 based on observations in the nonionizing UV and X-ray, assumptions about the nature of the scattering medium, and comparisons to AGN with nuclei that can be observed more directly. The results of these two papers are similar; we have chosen a SED similar to that assumed by Pier et al. (1994) since it is the simpler of the two. It consists of a broken power, \( F_\nu = K \nu^{-\alpha} \), where

\[
\alpha = 1.6, \quad 13.6 \text{ eV} \leq h\nu < 2000 \text{ eV}, \quad (3)
\]

\[
\alpha = 0.5, \quad h\nu \geq 2000 \text{ eV}. \quad (4)
\]

In addition, we have taken the observed fluxes at log \( \nu = 15.376 \) and 17.684, quoted by the authors, and assumed the same value for the fraction of intrinsic light reflected into our line of sight, \( f_{\text{rel}} = 0.015 \). Integrating over frequency and dividing by \( f_{\text{rel}} \) yields a luminosity of 4 × 10⁵⁴ s⁻¹, which is typical of Seyfert 1 nuclei.

As mentioned above, the range of emission lines seen in the spectra of each of these regions indicate a mix of physical conditions. Although emission from a wide range of ionization states is possible from a single component characterized by one atomic density, the most highly ionized parts of such a region would have the highest emissivity (greatest electron density and temperature), and therefore would dominate the integrated spectrum. Since we see strong lines from both low- and high-ionization states, it is likely that the physical properties of the regions where these lines form are indeed different and that we are seeing emission from distinct regions.

An initial guess at temperature and density can be derived from the ratio of [O iii] λλ5007, 4959/[O iii] λ4363 (Osterbrock 1974). Averaged over the four spectra, this ratio is ~46, which indicates a temperature in excess of 20,000 K in the low-density limit. It is difficult to obtain such a high electron temperature in the O + + zone in photoionized gas. It is possible that we are seeing a modest modification of this ratio by collisional effects. If we assume a density of 1 × 10⁵ cm⁻³, the observed [O iii] line ratio yields a temperature equal to 17,000 K, which is more characteristic of the O + + in photoionized gas. Therefore we assign this density to one component in these models. It is important, however, to note that this simple assumption may not be correct if mechanisms other than photoionization contribute to the thermal balance in the emission-line gas, as we shall discuss in § 7.

The gas in which the bulk of the [N ii] emission is formed must be characterized by a lower ionization parameter. There are three ways in which \( \dot{U} \) can be lowered: increase \( \dot{L} \), increase \( N_{\text{H}} \), or decrease \( L \). Since the individual regions are small (~20 pc) and a few tens of parsecs away from the putative central source, there cannot be sufficient range in distance to account for this drop. Since the O + + region is best characterized by a density of 10⁵ cm⁻³, increasing the density of the lower excitation gas would weaken the [N ii] emission owing to collisional de-excitation. The simplest explanation is that the low-excitation gas must see a different ionizing continuum. Although one possibility is local sources of ionizing radiation (Axon et al. 1998), we propose an alternative. The low-ionization (N +) gas is screened from the central source by the O + + gas, and it is therefore ionized by a filtered continuum. Gas of the same, or lower, density will then be in a lower state of ionization. Ferland & Mushotzky (1982) proposed that the NLR of NGC 4151 is illuminated by radiation that is partly absorbed by the broad-line region (BLR) gas (the so-called “leaky absorber” model). The leaky absorber SED is much harder than the intrinsic SED of the galaxy, and the conditions in the NLR gas are strongly influenced by the affects of X-ray ionization. Collisional excitation of Lyα and Hα become important processes in such gas. Also, extended partially ionized zones can form. Evidence for both of these effects can be seen in this set of spectra. The larger than case B Hα/Hβ ratio is most likely due to collisional enhancement of Hα. Also, if the emissivity of the gas in which the [N ii] lines form is low compared to that in which the higher excitation
lines form, there must be a large volume of it to produce low-excitation lines of comparable strength. We found in generating these models that placing gas of lower density behind the O$^+$ region was more likely to produce extended zones of $N(H^+)$/$N(H)$ $\approx$ 25%. At very low density the emissivity of the gas was so low that the emitting regions had to be much larger than the sizes of the regions observed. Note that, in this type of model, the covering factor of the low-excitation gas must be the same as the high-excitation gas, so the area of this component is constrained. We found that this component could be best modeled by assuming a density of $5 \times 10^4$ cm$^{-3}$, and an input spectrum filtered through a column density of $\sim 2 \times 10^{21}$ cm$^{-2}$.

Finally, there must be another component in which the highest excitation lines, in particular N v $\lambda$1240, arise. For the sake of simplicity, we assigned the same density to this component as used for the low-excitation gas ($5 \times 10^4$ cm$^{-3}$). Although this is arbitrary, it does produce a simple and self-consistent model. Specifically, there is a component of gas of density $5 \times 10^4$ cm$^{-2}$ that is partially shielded from the central source by a higher density component. The high-density gas is relatively optically thick but physically thin ($\sim 10^{-2}$ pc). The covering factors of the high-density component and the shielded gas are equal. The relative covering factors of the high-density gas and the unshielded lower density gas may vary among the regions.

In each of the four spectra, the ratio Ly$\alpha$/H$\beta$ is less than 20. The low-density ratio from recombination is 24. Therefore, it is likely that dust mixed in with the emission-line gas is responsible for the destruction of the Ly$\alpha$ photons. The strengths of the other resonance lines, specifically N v $\lambda$1240 and C iv $\lambda$1550, indicate that there cannot be much dust in the most highly ionized gas. Furthermore, from the presence of the Fe$^{+6}$ and Mg$^+$ lines we infer that the depletion of these refractory elements into grains cannot be near total, as it is in the Galactic interstellar medium (Seab & Shull 1983). Therefore, we have assumed different dust fractions in each of the three components in this model, as suggested by Netzer (1997). The highest ionization gas is dust-free. The low-ionization gas has a fraction of graphite dust 30% of that found in the Galactic interstellar medium. The medium ionization component is quite dusty, with a dust fraction of graphite and silicate dust 75% and 50% of the Galactic value, respectively. The depletions of carbon, oxygen, silicon, magnesium, and iron are scaled by these dust fractions, assuming Galactic interstellar medium values: 80% for carbon, 20% for oxygen, and complete depletion for the refractory elements. The dust fractions assumed are arbitrary, but the model results are not particularly sensitive to the exact fraction of the different types of dust. The main point for these models is that assuming a mix of dusty and dust-free gas yields the best fit to the observed line ratios.

5. MODEL RESULTS

Our approach in modeling these regions in NGC 1068 was to fit the O$^{++}$ emission gas first, and then to add the low-excitation component. This was, of course, necessitated by the fact that we have assumed the low-excitation gas is ionized by a continuum filtered by the O$^{++}$ component. Once these two models were complete, we added the third component primarily to fit the N v $\lambda$1240 line. Having arrived at the densities of these three components as described above, we set the ionization parameters for the models. In order to avoid adding additional components, we set the ionization parameter high enough for the O$^{++}$ that there would be significant [Ne v] and [Fe vii] emission; specifically, $U = 10^{-1.3}$, which, given the derived luminosity in ionizing photons, sets the distance from the central source at 15 pc. The four pointings in this set of data span a region of $\sim 70$ pc from the central source. Given the uncertainty in the actual location of the source and the value of the fraction of reflected continuum (Pier et al. 1994), the choice of distance is plausible and puts our model region right in the middle of the set of FOS pointings. At this distance, the high-ionization component is characterized by an ionization parameter, $U = 10^{-1}$.

It is clear from the SED of the ionizing continuum and the observed He ii $\lambda$4686/H$\beta$ ratio that much of the gas in these regions is optically thin at the Lyman limit. For optically thick gas, a simple photon counting calculation (see, e.g., Kraemer et al. 1994) yields a $\lambda$4686/H$\beta$ ratio of $\sim 0.16$; observed values range from 0.43 to 0.59. The presence of a large fraction of optically thin (matter-bounded) gas would increase the relative strength of the highest ionization lines in the composite spectrum compared to the composite spectrum from a region composed entirely of optically thick (radiation-bounded) gas. This is supported by the fact that the strongest relative [Ne v] $\lambda$3426 emission is seen in the same region that has the strongest He ii $\lambda$4686. There is no definitive way to determine the exact optical (and physical) thickness of each component of emission-line gas in these regions. We decided, a priori, to truncate the integration in the O$^{++}$ component at an optical depth of 10 at the Lyman limit. The resulting filtered spectrum is presented in Figure 5 and shows complete absorption at the He ii Lyman limit and strong absorption at the hydrogen Lyman limit; the physical conditions in gas photoionized by this continuum will be strongly affected by X-ray ionization and heating processes, as noted above. The resulting ionization parameter for the shielded gas was $10^{-2.35}$, with most of the energy in X-rays. We truncated the integration for the shielded component when the ionized fraction of the gas dropped below 5% and there was no longer significant line emission generated other than [N i] $\lambda$5200 and [O i] $\lambda\lambda$6300 and 6364, neither of which are strong in these data.

![Fig. 5.—Comparison of incident ionizing flux spectrum at the illuminated face of a directly photoionized cloud to the filtered flux spectrum used for the shielded model component.](image-url)
Since the relative contributions from the O°°+ and shielded components are linked, there is at least some basis for truncating the integration of the O°°+ at the chosen optical depth. Picking the point to truncate the integration of the high-ionization component is somewhat more arbitrary. We chose to truncate the model when we reached an optical depth of 10 at the He II Lyman limit, although there are indications from the predicted line ratios this component might be even thinner.

The results of the three-component models are given in Table 3, along with the composite spectrum line ratios and a dereddened "observed" spectrum averaged over the four sets of observations. The relative contributions to the composite spectrum are as follows: 25% from the high-ionization component, 50% from the O°°+ component, and 25% from the shielded component. We can check the plausibility of these ratios by comparing the total Hβ emission from each component. We only know one dimension of these slabs: the physical depth from the ionized face to the point where we truncated the integration. Comparing the product of the physical depth and the average emissivity gives a measure of the possible contribution from each component. The ratio of this product for the O°°+ and high-ionization component is ~2, which implies comparable covering factors for each of these components and supports the ratio of relative contribution used for the composite spectrum. The ratio of the products from the O°°+ and shielded components is ~4, or approximately twice the

### Table 3

| Element | High Ionization | O°°+ | Shielded | Composite | Average Observed |
|---------|----------------|------|----------|-----------|------------------|
| C III | 8977 | 0.41 | 0.17 | 0.11 | 0.22 | ... |
| N II | 2990 | 0.17 | 0.20 | 0.05 | 0.16 | ... |
| O VI | 1036 | 12.81 | 1.63 | 0.00 | 4.01 | ... |
| O V | 1216 | 8.26 | 2.08 | 0.01 | 3.11 | ... |
| N V | 1240 | 33.54 | 4.55 | 27.59 | 17.56 | 14.69 |
| Si IV | 1398 | 22.04 | 1.48 | 0.02 | 6.25 | 8.15 |
| Si IV | 1398 | 0.03 | 0.02 | 0.17 | 0.05 | incl w/O IV |
| O IV | 1402 | 4.53 | 2.39 | 0.01 | 2.33 | 1.88 |
| N IV | 1486 | 7.65 | 5.26 | 0.46 | 4.63 | 1.46 |
| C IV | 1550 | 28.12 | 1.67 | 1.38 | 8.21 | 8.86 |
| He II | 2164 | 7.62 | 3.83 | 0.21 | 3.85 | 3.48 |
| O II | 3166 | 0.55 | 1.16 | 0.97 | 0.95 | 0.38 |
| N II | 1750 | 0.66 | 1.58 | 1.14 | 1.23 | 0.64 |
| Si II | 1892 | 0.00 | 0.06 | 0.42 | 0.14 | incl w/C III |
| C III | 1909 | 1.99 | 1.82 | 3.76 | 2.34 | 4.57 |
| O III | 2232 | 0.04 | 0.09 | 0.12 | 0.09 | incl w/C II |
| O II | 2326 | 0.00 | 0.02 | 2.17 | 0.55 | 1.05 |
| [Ne IV] | 2423 | 0.42 | 0.84 | 0.10 | 0.55 | 2.25 |
| [O II] | 2470 | 0.00 | 0.01 | 0.51 | 0.13 | 0.26 |
| Mg II | 2800 | 0.00 | 0.04 | 1.65 | 0.43 | 1.25 |
| [Mg v] | 2929 | 0.03 | 0.02 | 0.00 | 0.02 | 0.14 |
| [Ne v] | 2974 | 0.03 | 0.02 | 0.00 | 0.02 | 0.18 |
| He II | 3290 | 0.43 | 0.24 | 0.01 | 0.23 | 0.30 |
| [Ne v] | 3346 | 1.10 | 1.06 | 0.00 | 0.81 | 1.24 |
| [Ne v] | 3426 | 3.00 | 2.90 | 0.02 | 2.20 | 3.28 |
| [Fe v] | 3458 | 0.23 | 0.15 | 0.00 | 0.13 | 0.18 |
| [O III] | 3727 | 0.00 | 0.02 | 2.16 | 0.54 | 0.86 |
| [Fe v] | 3760 | 0.32 | 0.19 | 0.00 | 0.18 | 0.27 |
| [Ne v] | 3869 | 0.01 | 1.94 | 6.81 | 2.65 | 2.32 |
| [Ne v] | 3967 | 0.00 | 0.60 | 2.11 | 0.83 | 0.84 |
| [S II] | 4072 | 0.00 | 0.00 | 0.48 | 0.12 | 0.32 |
| Hδ | 4100 | 0.26 | 0.25 | 0.26 | 0.26 | 0.31 |
| Hγ | 4340 | 0.47 | 0.46 | 0.47 | 0.47 | 0.53 |
| [O III] | 4363 | 0.18 | 0.67 | 0.55 | 0.51 | 0.45 |
| He II | 4680 | 1.03 | 0.59 | 0.03 | 0.56 | 0.48 |
| Hβ | 4861 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| [O III] | 5007 | 4.34 | 22.77 | 29.88 | 19.75 | 15.50 |
| [N II] | 5198, 5200 | 0.00 | 0.00 | 2.51 | 0.63 | ... |
| [Fe v] | 5721 | 0.37 | 0.26 | 0.01 | 0.22 | 0.35 |
| He I | 5876 | 0.00 | 0.06 | 0.12 | 0.06 | 0.16 |
| [Fe v] | 6087 | 0.54 | 0.39 | 0.01 | 0.33 | 0.45 |
| [O I] | 6300 | 0.00 | 0.00 | 5.27 | 1.30 | 0.45 |
| [O I] | 6364 | 0.00 | 0.00 | 1.73 | 0.43 | 0.22 |
| [Fe x] | 6374 | 0.90 | 0.08 | 0.00 | 0.27 | incl w/O I |
| [N II] | 65548, 6584 | 0.00 | 0.11 | 16.89 | 4.23 | 4.87 |
| Hα | 6563 | 1.15 | 2.97 | 3.93 | 3.13 | 5.30 |
| [S II] | 6716, 6731 | 0.00 | 0.00 | 2.07 | 0.51 | 0.56 |

* Relative to Hβ.

1. U = 10⁻¹⁰, N_H = 5 × 10⁴, no dust.
2. U = 10⁻¹⁻¹, N_H = 1 × 10⁵, 50% silicate dust, 75% graphite dust.
3. U = 10⁻¹⁻², N_H = 5 × 10⁵, 50% graphite dust.
4. N_H = 10⁻¹⁻¹⁻²⁻¹⁻³, N_H = 5 × 10⁴, 30% graphite dust.
5. 25% from high ionization, 50% from O°°+, 25% from shielded.
6. Average = 12.5% each, nucleus, position 1; 25% each, position 2, position 3.
ratio used in the composite. Since these two components are restricted to the same covering factor, as described above, it would seem that we do not have enough of the shielded gas. One obvious explanation is that there is additional shielded gas “behind” the high-ionization component. There may be other explanations as well; we will address this in the following section.

Comparison of the composite line ratios with the averaged observed ratios in Table 3 shows good agreement for the majority of emission lines. In particular, these include the [Fe VII] lines, [Ne V] λ3426, [Ne III] λ3869, [N II] λ6584 and 6584, [O I] λ3727, [S II] λλ6716 and 6731, C IV λ1550, and N v λ1240. The fact that the model predictions are good for lines of such a wide range of ionization states indicates that our overall balance of high- and low-excitation gas is reasonable. Also, the model predictions support our assumptions about the elemental abundances, since relative strengths of the iron, neon, and nitrogen lines would all decrease if solar abundances were assumed for these elements. The [O I] λ5007/λ4363 ratio is also in good agreement with the observations, but this was to be expected since the choice of density and excitation parameter for the O+ + component was based on this ratio. The predicted ratio of the [O I] λλ6300/[O I] λ6364 + [Fe X] λ6374 is also in agreement with the observations, showing that the 6364 line is indeed blended with [Fe X], although the strength of these lines relative to Hβ is somewhat high. The predictions of the ratios of the He II lines to Hβ are also in good agreement with the observations, which support our inclusion of matter-bounded gas in the composite model.

From the model predictions we can determine the size of the emitting regions and the total amount of excited gas using the relative contributions given above and comparing them to total Hβ emission from the nucleus. Assuming that the distance to NGC 1068 is 20 Mpc and that the filling factor within the emitting region is unity, we obtain a minimum volume of ~1 pc³; this is quite reasonable given the 20 pc extent of each region and their apparent clumpiness (see Fig. 1). We compute an actual filling factor of ~10⁻⁴. The total mass of gas required is ~8000 M⊙, which is not unreasonable within such a volume.

Although we were able to obtain a reasonable fit to the data with this model, we would not suggest that this is a unique solution but rather a possible one. In addition to the problems of emissivity and covering factor of the shielded component, there are several discrepant emission-line ratios that we will address in the following section; however, from the success of this model, we can with some confidence make several statements about the physical conditions in these regions. First, the dominant source of ionization and heating is photoionization from the continuum radiation emitted by the central source. Second, the estimate of the intrinsic SED and luminosity of the central source by Pier et al. (1994) is approximately correct, including the reflection fraction. Third, there is a range of density within the emission-line gas, and some of the gas is dusty. Finally, it is likely that the elemental abundances in these regions are not solar.

6. MODEL DISCREpanCIES

As discussed in § 2, the data obtained with FOS are spatially resolved. This permitted us to adjust more parameters, in particular abundances, than we have in previous studies (see, e.g., Kraemer et al. 1998). The result of this flexibility is a better set of predicted line ratios than can usually be achieved with photoionization models, but there are still obvious discrepancies. These both show the limitations of these simple models and can be used to obtain additional physical insight. Although there are some weak lines that were not well fitted by the models (e.g., [Mg V] λ2829 and [Ne V] λ2974), the fluxes of the weakest lines were difficult to measure accurately. We will, therefore, concentrate on the discrepancies in the predicted strengths of the stronger lines.

There are three high-ionization UV lines for which the model predictions are most obviously discrepant: N IV λ1485, O III λ1664, and [Ne IV] λ2424. The former two are predicted too strong, by factors of 4 and 3, respectively. The [Ne IV] line is predicted too weak by a factor of 4. The N IV line is a strong coolant in both of the directly ionized components of the model. If the high-ionization component was truncated at a lower optical depth or was characterized by a higher ionization parameter, the N +3 zone would be smaller, which reduces the strength of the λ1485 line. This would also help reduce the relative strength of the O III λ1664 line. The problem is that it would worsen the fit for the [Ne V] and [Fe VI] lines. The weakness of the predicted [Ne IV] strength presents a different problem. With the SED assumed for these models, it takes a unique set of conditions to get a component in which the relative [Ne IV] strength is comparable to that observed. The contribution from such a component would be diluted by the other component spectra, still resulting in a relatively weak λ2424 line. One possible explanation is that the electron temperatures predicted by these models are too low. A higher electron temperature in the O++ component would increase the strengths of the collisionally excited lines. Combined with the more highly ionized, high-ionization component, the overall strength of the [Fe VII] and [Ne V] lines could be maintained, and [Ne IV] increased, while dropping the overall N IV and O III. Although at first glance this might present a problem for the [O III] λλ5007/λ4363 ratio, the increase in the relative λ4363 strength could be offset by lowering the density of the O+ + component. The question is: what is the source of this additional heating? We shall return to this question in the following section.

There are also discrepancies in the low-excitation lines that arise primarily in the shielded component. The most obvious problem is that the reddening-corrected Balmer decrement is much steeper than predicted by the models, although this is biased somewhat in the average of the observations by the extremely high NII/Hβ ratio seen in the position 3 spectrum. The predicted neutral oxygen lines are too strong, and the model predicts fairly strong [N I] emission, which we did not detect in the spectra. The Mg II λ2800 line is too weak by approximately a factor of 3. Finally, either the emissivity or size of the partially ionized zone in the shielded component is insufficient. If more ionizing energy were injected into this gas, all of these discrepancies would be mitigated. A larger ionization fraction would drop the relative strength of the neutral lines. Increased heating and ionization would increase the emissivity of the gas. And, if the energy injection were in the form of energetic particles or increased X-ray ionization, enhanced collisional excitation of neutral hydrogen would increase the ratio of Hα/Hβ.
7. DISCUSSION

Although photoionization by the central source is the dominant mechanism determining the physical conditions in these four regions, these simple models do not give the full picture of the underlying physics in the emission-line gas. There appears to be additional heating and/or ionization from some source other than the assumed ionizing continuum.

There is evidence that emission-line ratios in these regions are affected by processes other than pure photoionization. Kriss et al. (1992) have remarked on the surprising regions are affected by processes other than pure photoionization from some source other than the assumed ionizing gas. There appears to be additional heating and/or ionization within the NLR. Their models predict an increase in the temperature, ionization fraction, and physical size of partially ionized or neutral gas deep within a photoionized emission-line cloud, as well as the temperature and ionization fraction of the illuminated face of the cloud. In their simple model, relativistic electrons were able to penetrate up to column densities in excess of $10^{22}$ cm$^{-2}$, similar to the sizes of our model components. The plausibility of this explanation is supported by the fact that there is clearly a source for such energetic particles in the inner NLR, i.e., the radio jet, and that the spectrum of position 3 shows the largest H$\alpha$/H$\beta$ ratio.

8. CONCLUSIONS

We have analyzed UV and optical spectra of the Seyfert 2 galaxy NGC 1068, obtained with the FOS on HST, from four regions within the inner NLR. Although these data were taken before the installation of COSTAR, we were able to determine that the contamination from the abberated PSF did not significantly degrade the quality of the data obtained from two of the four pointings, which provided us with three relatively distinct regions. We have constructed photoionization models to match an averaged set of conditions from these regions. The predicted emission-line ratios fit the dereddened observed ratios for the large majority of emission lines, with the few exceptions noted in § 6. We were able to fit both permitted and forbidden lines and lines from a wide range of ionization states, e.g., N v, as well as [N ii], using a three-component model and a limited set of free parameters. Since these models are constrained by the best estimate of the underlying SED of the ionizing continuum and spatial information provided by the FOS data, we are confident that the general physical characteristics assumed in these models reflect the actual physical conditions in the NLR gas.

From our analysis and modeling of the spectra we can make several statements regarding the physical conditions in the inner NLR of NGC 1068. First of all, the dominant mechanism for ionizing the NLR gas is photoionization by continuum radiation from the central source. The estimates by Pier et al. (1994) and Miller et al. (1991) regarding the SED and intrinsic luminosity of the ionizing continuum are approximately correct. As noted by Netzer (1997) and Netzer & Turner (1997), the abundances in the emission-
line gas are not solar, although we found that enhancement of nitrogen was more likely than depletion of oxygen. Also, our models support the suggestion of Netzer (1997) that these regions include a mixture of dusty and dust-free gas.

There are two aspects of these models that provide us with additional insight into the physical conditions in the NLR. First, as we discussed in detail in the previous two sections, the electron temperatures, and perhaps the ionization states, predicted by the models are too low, although this is masked somewhat by our choice of initial conditions such as density. The most likely explanation, given the constraints on the SED, is that there is additional collisional heating and ionization. Kriss et al. (1992) have suggested that shock heating is an important process. Since additional heating and ionization are also needed in the partially ionized component, it may be that cosmic rays, perhaps associated with the radio jet, are the main source of additional energy. As shown by Ferland & Mushotzky (1984), relativistic electrons can penetrate through large column densities of atomic gas, affecting the extended, partially ionized envelope. The location of the four regions in our data set with respect to the radio jet, particularly position 3, supports the suggestion of a jet/cloud interaction, whether the additional heating is due to shocks, cosmic rays, or some combination of the two.

The other interesting aspect of the model is that the most likely source of the low-ionization emission lines is gas that is partially screened by an optically thin component, probably of higher density. In fact, if there is additional heating beyond that due to photoionization, the ratio of the densities of the screening component to the low-ionization gas may be even greater than assumed here (2:1). We would suggest that this density gradient is the result of material being swept up by the force of the jet, creating a thin wall of denser material nearest the ionizing source. This is in general agreement with the recent observations by Axon et al. (1998), which indicates that the gas with the strongest line emission lies along the direction of the radio jet, although this may be because of, in part, the collimation of the ionizing radiation.

Planned Guaranteed Time Observations and Guest Observer observations of NGC 1068 with the Space Telescope Imaging Spectrograph (STIS) on HST will provide optical and UV spectra data with improved spatial resolution over a larger section of the NLR. Better spatial resolution will permit us to examine conditions within these regions and may reveal more about their apparent inhomogeneity. From these data we can further examine the possibility of interaction between the radio jet and the ionized gas, including looking off the radio axis for NLR gas that may be unaffected by the jet. Such observations will go further in constraining the physical conditions and energy budget in the NLR. S. B. K., J. R. R., and D. M. C. acknowledge support from NASA grant NAG 5-4103.

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