SPATIALLY RESOLVED FAR-ULTRAVIOLET SPECTROSCOPY OF THE NUCLEAR REGION OF NGC 1068

WEI ZHENG, JUN-XIAN WANG, GERARD A. KRIS, DAVID SAHNOW, MARK ALLEN, MICHAEL DOPITA, ZLATAN TSvetanov, AND GEOFFREY BICKNELL

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ABSTRACT

We carry out high-resolution FUSE spectroscopy of the nuclear region of NGC 1068. The first set of spectra was obtained with a 30'' square aperture that collected all emission from the narrow-line region. The data reveal a strong broad O vi component of FWHM ~3500 km s^{-1} and two narrow O vi Li2031, 1037 components of ~350 km s^{-1}. The C iii 1977 and N ii 1991 emission lines in this spectrum can be fitted with a narrow component of FWHM ~1000 km s^{-1} and a broad one of ~2500 km s^{-1}. Another set of seven spatially resolved spectra was made using a long slit of 1.25'' x 20'' at steps of ~1'' along the axis of the emission-line cone. We find the following: (1) Major emission lines in the FUSE wavelength range consist of a broad and a narrow component. (2) There is a gradient in the velocity field for the narrow O vi component of ~200 km s^{-1} from ~2'' southwest of the nucleus to ~4'' northeast. A similar pattern is also observed with the broad O vi component, with a gradient of ~3000 km s^{-1}. These are consistent with the HST STIS findings and suggest a biconical structure in which the velocity field is mainly radial outflow. (3) A major portion of the C iii and N ii line flux is produced in the compact core. They are therefore not effective temperature diagnostics for the conical region. (4) The best-fit UV continuum suggests virtually no reddening, and the He ii (N1640)/(N1085) ratio suggests a consistently low extinction factor across the cone. At ~2' northeast of the nucleus there is a region characterized by (a) a strong Ly \alpha flux but normal C iv flux, (b) a broad O vi line, and (c) a significantly enhanced C iii flux.

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

1. INTRODUCTION

NGC 1068 is a prototypical Seyfert 2 galaxy. Because of its proximity (z = 0.0038) and brightness, it has been studied in nearly every possible detail. The polarimetric observation by Antonucci & Miller (1985), which reveals a Seyfert 1 spectrum in scattered light, suggests that the nucleus and its associated broad-line region (BLR) are obscured. This finding provides strong evidence for the unified theory in which viewing angles account for the differences between various active galactic nuclei (AGNs; Antonucci 1993).

The nuclear region of NGC 1068 harbors a variety of astrophysical phenomena. At the very center of the nucleus there is a bright, compact (<0.3'') region commonly referred as the “hot spot.” Within a few arcseconds from the nucleus, there are several bright and compact clouds that coincide with knots in the radio jets (Wilson & Ulvestad 1983; Evans et al. 1991). The narrow-line region (NLR) is conical in shape toward the northeast (Fig. 1) along a position angle of ~200° and with an opening angle of ~40°. Beyond a 6'' radius the surface brightness drops dramatically, and emission is dominated by two ringlike filaments at ~10'' and 15'' from the nucleus.

High spatial resolution spectroscopy of NGC 1068 has been carried out in the optical (Caganoff et al. 1991; Unger et al. 1992; Inglis et al. 1995; Emsellem et al. 2006; Gerssen et al. 2006), as well as in the UV (Caganoff et al. 1991; Kraemer & Crenshaw 2000a; Crenshaw & Kraemer 2000b; Cecil et al. 2002; Groves et al. 2004). From approximately 2'' southwest of the nucleus to 4'' northeast, emission lines exhibit multiple components (Cecil et al. 1990; Crenshaw & Kraemer 2000a): (1) major emission lines consist of narrow and broad lines; (2) broad lines are approximately 2500–4000 km s^{-1} wide, which may be linked to those that are found in polarized light and believed to be reflected light from the inner BLR; and (3) narrow lines consist of a pair of red and blue components. The [O iii] and [N ii] line profiles suggest that the separation of these two components varies across the conical NLR. In addition to an overall biconical ionization configuration, there are compact knots whose optical spectra resemble kinematically the associated absorption-line systems in quasars (Cecil et al. 2002; Crenshaw & Kraemer 2003; Crenshaw & Kraemer 2005). These line-emitting knots have blueshifted radial velocities up to 3000 km s^{-1} relative to the galaxy’s systemic velocity, contributing mostly to the emission-line flux but not the continuum. Between ~2.5'' and 4.5'' northeast from the nucleus, UV line emission is redshifted relative to the systemic value, a pattern that is interpreted as the expansion of the plasma in the radio lobe (Axon et al. 1998).

Several important emission lines in the far-UV (FUV) region between 912 and 1150 Å are observable only with specially crafted UV instruments. During the Astro-1 mission the Hopkins Ultraviolet Telescope (HUT) observed NGC 1068 with 18'' and 30'' apertures. The most striking features in the wavelengths below 1150 Å are the strong C iii 1997 and N iii 1991 lines. The line intensity ratios of C iii /I(1909)/I(1977) and N iii /I(1750)/I(1991) are temperature-sensitive, and the derived temperature is >25,000 K (Kriss et al. 1992), higher than the values expected for a region producing C iii and N iii emission by photoionization. The line ratios in NGC 1068 are similar to those of the Cygnus...
Observations of NGC 1068 were carried out with two modes between 2001 November 28 and December 2. The first set of data of 21,951 s was taken with a fixed pointing and the low-resolution (LWRS) square aperture of 30". With such a large aperture, the fluxes of the nuclear region are all collected (Fig. 2), even with the thermally induced mirror motions anticipated. The second set of observations was carried out in scanning mode across the conical emission-line region, with a total exposure of 94,434 s. A narrow HIRS slit at a position angle of 137° was used. Because of orbital constraints, we were not able to place the slit completely perpendicular to the conical axis. The slit actually makes an angle of ~97° with respect to the conical axis.

Fig. 2.—FUSE spectrum of NGC 1068 at full aperture (30" square). The data are binned to 0.1 Å. Propagation errors are plotted in the bottom panel. The effects of major geocoronal emission lines are marked with Earth symbols, and data at these wavelength bins are removed.

2. DATA

2.1. FUSE Data

FUSE covers a wavelength range between 904 and 1188 Å with a spectral resolution of R ~ 20,000 (Moos et al. 2000). It is based on a Rowland circle design and consists of four separate optical paths or channels. Each channel consists of a mirror coated with aluminum plus LiF or SiC; a focal plane assembly, which includes the spectrograph apertures; a diffraction grating coated with aluminum plus LiF or SiC; and a portion of the FUV detector (two named A and B). In all, data are collected from eight traces, and the pairs of A and B are called “channels.” Our original plan was to take spectra of the nuclear region of NGC 1068 at seven positions separated by ~1". Because of thermal instability of the optical structure in orbit, the four channels in the FUSE spectrograph are not perfectly aligned, with orbit-dependent drifts possibly as large as 6". Therefore, a new observing strategy was developed to counter the drifting effect. The high-resolution aperture (HIRS; 1.25" × 20") is used for spectroscopy on the finest spatial scales to ensure that maximum resolution is maintainable even if the telescope imaging or pointing stability degrades below specifications. Since the LiF1 channel is mounted on the same optical system as the FUSE fine error sensor, spatial knowledge and stability are fully available for the data from this channel.

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Over years of FUSE operation, a large amount of engineering data has been collected, and the drift pattern among the four channels has been well studied. After peak-up alignments of channels with a bright point source at the beginning of orbital nights, the relative drifts exhibit a dependence on orbital time (Fig. 3). The LiF2 channel exhibits relatively small drifts, within $1^\prime$ with respect to the LiF1 channel. The SiC channels exhibit drifts that can be represented by a constant drift rate during orbital nights. For example, the SiC2 channel drifts relative to the LiF1 channel at a rate of approximately $4^\prime$ per 30 minutes. The starting drift at the orbital sunset is, however, variable, depending on the degree of occultation, because the drift is generally in the reverse direction during orbital days.

NGC 1068 itself is too diffuse to appear in the guide-star camera. For target acquisition, we used an offset guide star $85^\prime$ from the nucleus. We also used a FUV-bright star, Feige 23, which is approximately $4^\prime$ away from the source, for instrumental peak-up alignments at the beginning of each pointing. One orbit of peak-up operation on Feige 23 was made to establish the drift pattern due to orbital motion. During the second orbit, one peak-up with the medium-resolution aperture (MDRS; $4^\prime\times 20^\prime$) and another with HIRS were carried out on Feige 23. The instrument was then pointed to the southwest part of the nucleus of NGC 1068, and we started observations in scanning mode. As shown in Table 1, each of the five HIRS pointings consisted of seven to nine orbits on the target. The observation window varied orbit by orbit, between $\sim 1200$ and $2600$ s. The scanning speed in each individual orbit was set to complete $10^\prime$ within the designated observation window. After accumulating a total exposure time of $\sim 18,000$ s, FUSE returned to Feige 23 and carried out one peak-up with MDRS and another with HIRS, then moved back to NGC 1068 for a new set of scans. After a total of five pointings, FUSE returned to Feige 23 for one last orbit of peak-up with MDRS to acquire additional information on the drift pattern. Since the channel alignments are not perfect except at the beginning of the first orbit, the orbit-time dependence of channel drifts derived from the engineering data is only useful in terms of the relative drift speed, not for the absolute timing.

The drifts in the SiC channels can be as large as $6^\prime$, which is near the size of the ionization cone. The drift direction is mainly along $+x$ on the FUSE aperture plate, i.e., along the conical direction of NGC 1068 at the desired FUSE aperture position angle of $\sim 105^\circ$. Therefore, the observation procedure was designed so that each observation starts $\sim 5^\prime$ from the nucleus in the anticone (southwest) direction and sweeps across the cone toward the northeast direction at a constant angular velocity. Figure 4 illustrates the time sequence in one orbit of observation: with a constant angular speed, the FUSE HIRS slit swept across the nuclear region of NGC 1068. We identified the peak position of the count rate in the LiF1 channel as the nuclear position. Based on the angular speed illustrated in Figure 3, seven time intervals were defined, and the spectral extraction in these segments yields the data A–G. Figure 4 (top) marks the segments for the LiF1 channel, whose spatial information is fully available. For the other three channels, their count rates peaked at different times as a result of drifting. We marked their respective peak positions. The sweeping speeds in these channels are the sum of two terms: that of the LiF1 channel plus the relative drift speed of each channel (Fig. 3) with respect to LiF1. Their time segments A–G are also illustrated in Figure 4. The observation results in a series of segments that are dependent on the relative positions with respect to the nucleus. In each time sequence, one can determine the time when the observation slits coincide with the nucleus, as determined by the peak in the count rate.

The LiF1 slit positions are illustrated in Figure 1. Seven sets of data are extracted with a relative shift of $1^\prime$ ($1.25^\prime$ at the nucleus), starting from $2^\prime$ southwest of the nucleus (in the opposite direction of the cone) to $\sim 4^\prime$ northeast of it. They were named A, B, C (the nucleus; see Fig. 1), D, E, F, and G. The significant astigmatism of FUSE yields a spatial resolution of $\sim 5^\prime$ at best; therefore,
it cannot be used like a normal long-slit spectrograph to dissect the fine details along its slit. Not all the segment data are extracted; if a time segment is incomplete (i.e., G in Fig. 4), they are not used.

Four pairs of spectra were derived from the FUSE channels. Each pair of A and B data is subject to the same normalization factor. We used the O\textsuperscript{vi} emission flux, which is common to all four channels, to normalize the spectra to the level in LiF1A. We first calculated the continuum level between 1050 and 1070 Å for LiF2B, SiC1A, SiC2B, and LiF1A, then subtracted it from the spectrum to enable the measurement of emission-line fluxes. We then calculated the O\textsuperscript{vi} flux in two bins: a narrow component between 1041.1 and 1043.6 Å and a broad component between 1027 and 1048 Å. The flux ratios with respect to their values in the LiF1A spectrum were calculated, and their mean values were used as the normalization factors (Table 2). For the first set of data, taken with LWRS, we corrected the “worm effect” in the LiF1A,B channel according to the procedures described in the FUSE Instrument and Data Handbook.\textsuperscript{8}

FUSE data reduction was carried out with the pipeline version CALFUSE 2.3 with specific timing flags to extract time-dependent (hence, position-dependent) segments of spectra in eight traces. The FUSE spatial resolution is 1.5”, and the spacecraft jitter, as determined from the FUSE engineering data, is approximately 0.6”. The total spatial resolution is therefore 1.6”. Since the data were obtained with a 1.25” slit, there is overlap between positions. This can be seen by the fact that the sum of the fluxes in all positions is larger than that taken with one large 30” aperture.

The normalized spectra in the four channels are binned to 0.1 Å and then merged, weighted by their signal-to-noise ratios (S/Ns). The merged spectra at the seven slit positions are plotted in Figure 5. The wavelength bin between ~1077 and 1087 Å falls into a gap between the LiF channels, and only data in the SiC2B channel exist.

### 2.2. HST Data

We retrieved archival HST STIS spectroscopic data to complement our FUSE data. Two sets of UV spectra are available: one taken at a position angle of 218° and four adjacent slit positions of 0.2” × 52” (STIS-A; Cecil et al. 2002), and another at a position angle of 202° taken with a slit of 0.1” × 52” (STIS-B; Crenshaw & Kraemer 2000b). Both sets (see Fig. 1) contain data taken with gratings G140L and G230L covering a wavelength range of ~1150–3170 Å at a resolution of R ~ 1000. These STIS observations were made between 1988 and 2000 and are therefore not simultaneous with the FUSE data. For STIS-A, we

![Figure 4](http://fuse.jhu.edu/analysis/dhbook.html)

**Table 2**

| Position | LiF1A | LiF2A | SiC1B | SiC2B | STIS |
|----------|-------|-------|-------|-------|------|
| A        | 1.00  | 1.51  | 0.86  | 2.48  | 2.50 |
| B        | 1.00  | 1.42  | 0.97  | 1.70  | 2.03 |
| C        | 1.00  | 1.17  | 1.03  | 1.07  | 1.74 |
| D        | 1.00  | 1.29  | 0.96  | 1.29  | 2.28 |
| E        | 1.00  | 1.15  | 0.78  | 0.87  | 3.95 |
| F        | 1.00  | 1.10  | 1.28  | 1.17  | 4.84 |
| G        | 1.00  | 1.51  | 2.75  | 1.83  | 6.05 |

![Figure 5](http://fuse.jhu.edu/analysis/dhbook.html)

**Table 2**

| Flux Normalization Factor |
|---------------------------|
| Position | LiF1A | LiF2A | SiC1B | SiC2B | STIS |
|----------|-------|-------|-------|-------|------|
| A        | 1.00  | 1.51  | 0.86  | 2.48  | 2.50 |
| B        | 1.00  | 1.42  | 0.97  | 1.70  | 2.03 |
| C        | 1.00  | 1.17  | 1.03  | 1.07  | 1.74 |
| D        | 1.00  | 1.29  | 0.96  | 1.29  | 2.28 |
| E        | 1.00  | 1.15  | 0.78  | 0.87  | 3.95 |
| F        | 1.00  | 1.10  | 1.28  | 1.17  | 4.84 |
| G        | 1.00  | 1.51  | 2.75  | 1.83  | 6.05 |

The nucleus is at position C.
FIG. 6.—STIS spectra extracted at different windows that correspond to the respective FUSE slits. Fluxes are normalized to the corresponding FUSE data.

We only used three slit positions, as the other does not have G140L data. The fluxes in the three extracted spectra are summed.

Since the FUSE spatial resolution (≥5″ along its slit) is considerably lower than that of STIS, and since the position angles of these two sets of observations are nearly perpendicular, we must normalize the STIS data to those of FUSE. Using the continuum level around 1180 Å in these spectra does not result in satisfactory matches, as the line/continuum ratios are not constant at these spatial scales across the nucleus. We therefore use HST WFPC2 images retrieved from MAST to determine the normalization factor between STIS and FUSE data.

To extract the STIS spectra, we first smoothed the two-dimensional images by 30 pixels (0.67″) with a Gaussian kernel along the spatial direction of the FUSE scans to match the spatial resolution of the corresponding FUSE data. We then ran the standard STIS pipeline task x1d with steps of 1″ (1.25″ at the nucleus) that corresponded to the respective moving FUSE slit positions and a slit width of 1.25″. To normalize the STIS fluxes, we used a HST WFPC2 image of NGC 1068, taken with filter F218W, and smoothed it along the same direction with the same kernel size as the STIS two-dimensional image. We then measured the flux in each STIS window. To normalize the FUSE fluxes, we smoothed the WFPC2 image to the FUSE resolution, namely, 0.67″ and 5″, respectively, along the directions perpendicular and parallel to that of the FUSE slit (Fig. 1). The flux ratios in respective extraction windows were used to derive the normalization factors (Table 2). To the northwest of the source, there are several bright spots whose fluxes may be picked up because of FUSE’s low spatial resolution along its slit. We tested using several extraction windows that are short enough not to include the fluxes from these bright spots in the smoothed WFPC2 image. Since it is unlikely that these bright spots contribute to the redshifted UV emission lines, we used the flux values measured in a short window in calculating the scaling factor. Any uncertainties introduced by this window selection only affect the scaling of Lyα and C iv in positions A and G.

Since the FUSE slit positions are accurate to ~0.3″, we measured the fluxes in the neighboring regions to make sure that the normalization factors are accurate to at least 20%. The height of the STIS extraction windows is the same as that of FUSE (∼1″), but their widths (0.1″–0.2″) are much smaller than FUSE (20″). Therefore, considerable STIS normalization factors were applied. The matching STIS spectra are plotted in Figure 6.

We compared extracted spectra from the STIS-A and STIS-B data sets, and their line ratios are comparable within 25%. In the following section, we only use the data from STIS-A, as they cover a spatial region 6 times as wide (0.2″ × 3″) as that of STIS-B.

3. FITTING

Spectral analyses were carried out using the IRAF task specfit (Krisi 1994). For the FUSE spectrum taken with a large aperture, we used a pair of narrow components and one broad component in the O vi emission-line profile. Each narrow O vi component was modeled as a doublet whose wavelengths ratio is fixed by atomic data and whose line widths are identical. The O vi emission feature is heavily absorbed by interstellar absorption at ∼1037 Å; therefore, we introduced several absorption components. The Lyβ emission is not prominent, and it is often overwhelmed by the broad O vi emission. Only in one or two positions is the Lyβ emission visible. We therefore only

| Emission Line | λ      | Flux  | FWHM  | Velocity |
|---------------|--------|-------|-------|----------|
|               | (Å)    | (10⁻¹⁴| (km s⁻¹)| (km s⁻¹) |
| C iii narrow  | 977.02 | 46.2  | 720   | 28 ± 16  |
| C iii broad   | …      | 10.1  | 3489  | 1047 ± 544 |
| N iii narrow  | 990.98 | 19.8  | 934   | 381 ± 47 |
| N iii broad   | …      | 28.5  | 3393  | 1371 ± 431 |
| Lyβ           | 1025.72| 28.4  | 3392  | 1340 ± 46 |
| O vi narrow r.| 1037.63| 41.1  | 390   | 290 ± 6  |
| O vi narrow b.| …      | 59.7  | 340   | 76 ± 4   |
| O vi broad    | 1034.00| 338   | 3584  | 52 ± 61  |
| He ii narrow  | 1085.15| 45    | 993   | 167 ± 16 |
| He ii broad   | …      | 14.4  | 4286  | −3912 ± 354 |

* Corrected for $E_{B-V} = 0.00$.

* With respect to the systemic redshift $z = 0.0038$ km s⁻¹.
| Line          | Position A | Position B | Position C | Position D |
|--------------|------------|------------|------------|------------|
|              | Å          | Flux^a      | FWHM^[b]   | Velocity^[b] |
|              | (10^-14 ergs s^-1 cm^-2) | (km s^-1) | (km s^-1) | |
| C iv         | 977.02     | 2.3 ± 1.5  | 564 ± 243 | 604 ± 198  |
| N iii narrow  | 990.98     | 2.0 ± 1.0  | 230 ± 108 | 140 ± 60   |
| N iii broad   | 1025.72    | 0.7 ± 0.4  | 878 ± 0   | 257 ± 192  |
| Ly/β         | 1037.63    | 7.9 ± 0.6  | 655 ± 38  | 376 ± 6    |
| O vi narrow   | 1034.00    | 7.8 ± 0.8  | 3131 ± 488 | 1192 ± 207 |
| O vi broad    | 1085.15    | 3.1 ± 1.0  | 1098 ± 968 | 16 ± 116   |
| Lyα narrow   | 1215.67    | 37.1 ± 2.8 | 1580 ± 96 | 393 ± 37   |
| Lyα broad    | 1549.50    | 18.8 ± 6.5 | 1432 ± 95 | 374 ± 96   |
| C iv narrow   | 1640.46    | 9.8 ± 0.7  | 1858 ± 234| 390 ± 67   |
| C iv broad    | 1750.00    | 0.3 ± 0.5  | 1818 ± 1916 | 3691 ± 1758 |
| C iii narrow  | 1908.73    | 6.8 ± 1.3  | 2111 ± 228 | 43 ± 72    |
| C iii broad   | 9.4 ± 1.3  | 6883 ± 1106 | −535 ± 348 | |
|              |            |            |            |            |
| C iv         | 977.02     | 14.1 ± 3.5 | 596 ± 290 | −31 ± 55   |
| N iii narrow  | 990.98     | 8.8 ± 3.5  | 1048 ± 351| 519 ± 190  |
| N iii broad   | 1025.72    | 2.4 ± 2.7  | 2005 ± 2083 | 2332 ± 1454 |
| Ly/β         | 1037.63    | 5.2 ± 1.0  | 878 ± 0   | −2 ± 105   |
| O vi narrow   | 1034.00    | 23.9 ± 5.1 | 385 ± 34  | 333 ± 12   |
| O vi broad    | 1085.15    | 10.2 ± 1.5 | 1108 ± 177| −18 ± 74   |
| Lyα narrow   | 1215.67    | 158.2 ± 0.4| 1528 ± 18 | 366 ± 10   |
| Lyα broad    | 1549.50    | 119.9 ± 7.8| 7676 ± 787| 366 ± 0    |
| C iv narrow   | 1640.46    | 47.0 ± 1.6 | 1872 ± 66 | −234 ± 31  |
| C iv broad    | 1750.00    | 4.1 ± 1.0  | 1848 ± 569| 299 ± 169  |
| C iii narrow  | 1908.73    | 29.6 ± 2.4 | 2229 ± 95 | −126 ± 27  |
| C iii broad   | 36.7 ± 2.2 | 6296 ± 408 | −678 ± 110 | |
|              |            |            |            |            |
| C iv         | 977.02     | 38.6 ± 4.3 | 911 ± 99  | −7 ± 49    |
| N iii narrow  | 990.98     | 11.0 ± 10.3| 989 ± 558 | −8 ± 202   |
| N iii broad   | 1025.72    | 29.0 ± 14.8| 3207 ± 767| 870 ± 770  |
| Ly/β         | 1037.63    | 12.6 ± 2.9 | 878 ± 132 | −84 ± 61   |
| O vi narrow   | 1034.00    | 46.2 ± 6.3 | 333 ± 22  | 290 ± 9    |
| O vi broad    | 1085.15    | 17.0 ± 1.7 | 1149 ± 116| −70 ± 55   |
| Lyα narrow   | 1215.67    | 278.5 ± 4.7| 1352 ± 21 | 395 ± 7    |
| Lyα broad    | 1549.50    | 253.3 ± 13.5| 9104 ± 641| 395 ± 0    |
| C iv narrow   | 1640.46    | 167.6 ± 9.9| 1472 ± 59 | 172 ± 19   |
| C iv broad    | 1750.00    | 131.0 ± 9.8| 4193 ± 244| −390 ± 35  |
| He ii         | 1908.73    | 38.4 ± 4.4 | 1902 ± 107| −270 ± 28  |
| C iii narrow  | 38.3 ± 4.0 | 5053 ± 219 | −672 ± 56  | |
| C iii broad   | 977.02     | 31.2 ± 3.2 | 900 ± 0   | 183 ± 52   |
| N iii narrow  | 990.98     | 11.1 ± 3.3 | 888 ± 243 | 372 ± 93   |
| N iii broad   | 1025.72    | 44.1 ± 71.1| 5775 ± 3455| −3804 ± 4077 |
| Ly/β         | 1037.63    | 6.2 ± 1.8  | 878 ± 0   | −46 ± 0    |
| O vi narrow   | 1034.00    | 14.9 ± 0.9 | 380 ± 31  | 287 ± 9    |
| O vi broad    | 1085.15    | 15.6 ± 1.2 | 940 ± 85  | 21 ± 36    |
| He ii         | 1215.67    | 291.4 ± 14.3| 1248 ± 42 | 388 ± 7    |

**TABLE 4**  
**UV EMISSION LINES AT POSITIONS A–G**
### TABLE 4—Continued

| Line                  | Å   | Flux$^a$ $(10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2})$ | FWHM$^b$ $(\text{km s}^{-1})$ | Velocity$^{b,c}$ $(\text{km s}^{-1})$ |
|-----------------------|-----|------------------------------------------------------|-------------------------------|----------------------------------------|
| Ly$\alpha$ broad      | ... | 145.9 ± 10.6                                        | 5718 ± 1708                   | 388 ± 0                                 |
| C iv narrow           | 1549.50 | 143.7 ± 18.7                                      | 1777 ± 125                    | 6 ± 21                                  |
| C iv broad            | ... | 105.9 ± 18.4                                        | 3388 ± 130                    | −793 ± 17                               |
| He ii                 | 1640.46 | 88.6 ± 3.4                                         | 1928 ± 73                     | −504 ± 35                               |
| N m 156985            | 1750.00 | 9.1 ± 2.3                                          | 2415 ± 404                    | 15 ± 188                                |
| C iii narrow          | 1908.73 | 45.3 ± 2.9                                         | 2181 ± 493                    | −367 ± 114                              |
| C iii broad           | ... | 58.8 ± 0.0                                          | 5201 ± 0                      | −877 ± 39538                           |

Position E

| C iii                 | 977.02 | 17.7 ± 4.2                                         | 1149 ± 412                    | 27 ± 119                                |
| N ii narrow           | 990.98 | 6.7 ± 2.6                                          | 577 ± 177                     | 375 ± 84                                |
| N ii broad            | ... | 12.9 ± 15.0                                        | 2584 ± 2236                   | −764 ± 1615                             |
| Ly$\beta$             | 1025.72 | 3.6 ± 1.2                                          | 878 ± 0                       | 68 ± 0                                  |
| O vi narrow           | 1037.63 | 13.0 ± 1.2                                        | 639 ± 42                      | 252 ± 17                                |
| O vi broad            | 1034.00 | 52.9 ± 2.9                                         | 3145 ± 168                    | −475 ± 78                               |
| He ii                 | 1085.15 | 12.1 ± 0.8                                        | 818 ± 58                      | 208 ± 25                                |
| Ly$\alpha$ broad      | 1215.67 | 359.0 ± 9.4                                        | 1265 ± 24                     | 474 ± 7                                 |
| Ly$\beta$             | ... | 72.4 ± 6.4                                         | 4953 ± 1166                   | 474 ± 0                                 |
| C iv narrow           | 1549.50 | 107.2 ± 10.9                                       | 1812 ± 141                    | 79 ± 71                                 |
| C iv broad            | ... | 63.5 ± 11.0                                        | 3241 ± 134                    | −981 ± 99                               |
| He ii                 | 1640.46 | 64.0 ± 2.9                                         | 4490 ± 157                    | 1112 ± 5                                |
| N m 156985            | 1750.00 | 9.1 ± 1.6                                          | 2986 ± 549                    | 362 ± 237                               |
| C iii narrow          | 1908.73 | 30.3 ± 4.2                                         | 2185 ± 135                    | 82 ± 55                                 |
| C iii broad           | ... | 39.3 ± 4.3                                         | 4489 ± 251                    | −1026 ± 162                             |

Position F

| C iii                 | 977.02 | 15.8 ± 4.3                                         | 900 ± 270                     | 424 ± 119                               |
| N ii narrow           | 990.98 | 7.1 ± 5.8                                          | 1056 ± 625                    | 164 ± 289                               |
| N ii broad            | ... | 8.0 ± 9.4                                          | 3540 ± 1540                   | 333 ± 1681                              |
| Ly$\beta$             | 1025.72 | 9.0 ± 0.7                                          | 878 ± 0                       | 257 ± 47                                |
| O vi narrow           | 1037.63 | 11.4 ± 1.9                                         | 219 ± 30                      | 152 ± 17                                |
| O vi broad            | 1034.00 | 96.1 ± 15.6                                        | 1785 ± 16                     | 456 ± 20                                |
| He ii                 | 1085.15 | 8.3 ± 0.7                                          | 665 ± 66                      | 266 ± 25                                |
| Ly$\alpha$ broad      | 1215.67 | 299.6 ± 9.6                                        | 1223 ± 33                     | 520 ± 10                                 |
| Ly$\beta$             | ... | 46.8 ± 7.4                                         | 4582 ± 1014                   | 520 ± 0                                 |
| C iv narrow           | 1549.50 | 73.3 ± 5.9                                         | 1181 ± 72                     | 313 ± 29                                |
| C iv broad            | ... | 34.7 ± 5.3                                         | 3365 ± 323                    | −461 ± 178                              |
| He ii                 | 1640.46 | 42.6 ± 2.8                                         | 1132 ± 74                    | 305 ± 13                                 |
| N m 156985            | 1750.00 | 4.7 ± 1.6                                          | 1289 ± 702                    | 1040 ± 211                              |
| C iii narrow          | 1908.73 | 29.1 ± 1.2                                         | 1500 ± 77                     | 400 ± 41                                |
| C iii broad           | ... | 14.3 ± 0.9                                         | 3848 ± 392                    | −1679 ± 139                             |

Position G

| C iii                 | 977.02 | 12.5 ± 5.4                                         | 344 ± 133                     | 91 ± 80                                 |
| N ii narrow           | 990.98 | 8.7 ± 4.2                                          | 833 ± 398                     | 417 ± 148                               |
| N ii broad            | ... | 10.8 ± 58.4                                        | 3237 ± 7653                   | −2085 ± 9897                           |
| Ly$\beta$             | 1025.72 | 4.3 ± 0.9                                          | 878 ± 0                       | −61 ± 93                                |
| O vi narrow           | 1037.63 | 13.3 ± 2.6                                         | 372 ± 16                      | 189 ± 14                                |
| O vi broad            | 1034.00 | 37.6 ± 4.9                                         | 2852 ± 422                    | 416 ± 95                                |
| He ii                 | 1085.15 | 7.5 ± 1.4                                          | 617 ± 105                     | 150 ± 58                                |
| Ly$\alpha$ broad      | 1215.67 | 152.2 ± 5.8                                        | 1208 ± 35                     | 523 ± 12                                 |
| Ly$\beta$             | ... | 32.2 ± 3.9                                         | 4627 ± 848                    | 523 ± 0                                 |
| C iv narrow           | 1549.50 | 50.8 ± 3.0                                         | 1227 ± 62                     | 251 ± 27                                |
| C iv broad            | ... | 19.5 ± 2.3                                         | 4877 ± 581                    | −283 ± 216                              |
| He ii                 | 1640.46 | 28.0 ± 1.7                                         | 1047 ± 58                     | 265 ± 29                                |
| N m 156985            | 1750.00 | 1.5 ± 0.8                                          | 708 ± 334                     | 1453 ± 195                              |
| C iii narrow          | 1908.73 | 12.5 ± 3.1                                         | 1797 ± 252                    | 333 ± 83                                |
| C iii broad           | ... | 12.4 ± 3.5                                         | 4491 ± 658                    | −870 ± 510                              |

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$^a$ With $E_B, r = 0.00$.  
$^b$ Values with zero errors are prefixed.  
$^c$ With respect to the systemic redshift $z = 0.0038 \text{ km s}^{-1}$.  

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modeled one component with a fixed line width. For N\textsc{iii} and C\textsc{iii} emission-line features, one narrow component and one broad component were included in the fitting. We fitted a power law with no extinction to the continuum. The fitted results are listed in Table 3.

For the \textit{FUSE} spectra taken at positions A–G, we used one narrow component plus one broad component to model the O\textsc{vi} emission, and we used one component for the N\textsc{iii} and C\textsc{iii} lines. To reduce the effect of channel drifts, the \textit{FUSE} spectra were fitted individually for each channel. The fitting results in Table 4 are primarily derived from the LiF1 data, which are not affected by channel drifts. For wavelengths below 995 Å, we used the fitting results from the scaled SiC2A channel, which extends to 1005 Å and is therefore less susceptible than the SiC1B channel to detector edge effects. For He\textsc{ii} k 1085, LiF2A data were used.

The fluxes of the fitted components were normalized by the values in Table 2 and then tabulated in Table 4. The profiles of four major emission lines at seven different slit positions are plotted in Figure 7, to show the changes in the narrow and broad components as a function of spatial location.

The UV spectra suggest a low extinction level. We first fitted the continuum in the wavelength windows that are free of emission and absorption lines, and the results suggest a power-law index of $\alpha = 0.90 \pm 0.04$ ($f_{\lambda} \propto \lambda^{\alpha}$) and an extinction of $E_{B-V} = 0.005 \pm 0.002$. As a comparison, the HUT spectrum between 912 and 1800 Å was fitted with a power-law continuum of $\alpha = 0.62 \pm 0.15$ and $E_{B-V} = 0.065 \pm 0.02$. If we adopt this extinction value, the power-law index is $\alpha = 0.85 \pm 0.06$. The similar power indices suggest that one single power-law continuum can fit the FUV spectrum of NGC 1068 without introducing significant reddening, as suggested from the UV/optical line ratios (Crenshaw & Kraemer 2000a).

4. DISCUSSION

Many previous studies have gradually unraveled the kinematical complexities of gas in the nuclear region of NGC 1068. The X-ray data (Kinkhabwala et al. 2002) suggest that emission lines are formed mainly in a photoionized plasma of a temperature around a few eV. The spatial resolution afforded by \textit{HST} leads to a picture of a decelerating jet (Das et al. 2006): a biconical outflow from the nuclear region sweeps up denser, ambient clouds in the ISM of NGC 1068. Other possibilities include overlapping, discrete ejection that gradually dissipates (Axon et al. 1998; Capetti et al. 1996, 1997). In addition, a high-velocity radio jet impinges on some of the clouds. Some gas expands perpendicularly to the axis of the jet, and the expanding radio lobe at the end of the jet also pushes on the ambient ISM. Near the nucleus, kinematic components span several thousand kilometers per second in velocity, and the continuum hot spot visible in \textit{HST} images reflects a polarized view of the broad lines in the active nucleus.

Our spatially resolved \textit{FUSE} observations, while not at the resolution of \textit{HST}, add information from major emission lines shortward of the \textit{HST} bandpass at high spectral resolution. We plot the fluxes of major UV emission lines from our observations at seven different slit positions in Figure 8 and list the fitted line properties in Table 4. In this section, we discuss the four emission lines in the \textit{FUSE} spectral range, along with a comparison to emission lines observed in the STIS spectra.

4.1. O\textsc{vi} Emission

The most prominent feature in the \textit{FUSE} spectra is the O\textsc{vi} $\lambda\lambda 1031, 1037$ emission line. In the data taken with LWRS, the
two narrow O vi components are of FWHM $\approx 350$ km s$^{-1}$ and a separation of $\approx 200$ km s$^{-1}$. In the seven spectra taken with a narrow slit, we resolve this blend into one narrow component with a FWHM of $\approx 350$ km s$^{-1}$ and one broad component. In Figure 9 we plot the O vi profiles at the seven different slit positions. The high spectral resolution of the FUSE data enables us to compare with the results of optical Fabry-Pérot spectroscopy (Cecil et al. 1990), which reveal a narrow core of $\approx 300$ km s$^{-1}$. According to the optical data, nearly 75% of the [N ii] $\lambda 6583$ flux is from components $\approx 1500$ km s$^{-1}$ wide. Line widths at such a scale are consistent with those derived from HST UV spectroscopy. The narrow-line flux in the FUSE spectra is highly concentrated (60%) at the compact core, suggesting that the “true” NLR probably remains unresolved at a subarcsecond scale. While the narrow O vi emission line is not the dominant component, its distribution is different from its broad counterpart, while only 40% of the broad O vi line flux is from slit position C.

It is surprising that the O vi emission is dominated by a component that is broader than those seen in polarized light. In the LWRS spectrum, more than three-fourths of the O vi flux is from a component with FWHM $\approx 3500$ km s$^{-1}$ that is blueshifted relative to the narrow component by $\approx 500$ km s$^{-1}$. This broad component is present in all seven FUSE slit spectra with considerable strength. It may arise from the reflected emission from the hidden BLR and/or may be the result of a significant velocity dispersion in the NLR. The HST Faint Object Camera data (Axon et al. 1998) reveal that emission lines near the hot knots 2$''$ northeast (FUSE slit positions D and E) are split into two velocity systems separated by $\approx 1500$ km s$^{-1}$. The STIS spectra discussed by Groves et al. (2004) show [O iii] emission knots spanning such a broad velocity range in the immediate vicinity of the nucleus, but not at distances of several arcseconds. Since the FUSE slit collects emission from a block of regions spanning several arcseconds perpendicular to the conical axis, the total line emission from these regions may be blended into one broad component.

The ratio of C iv/O vi may provide insight into the physical conditions of the line-emitting regions. The value is higher for the narrow components than their broad counterparts, implying a range of the ionization parameter $U \approx 0.05$–1.0 in a typical photoionization calculation. High values of $U > 1$ are consistent with models that assume the same origin for the associated absorbers and BLR (Kriss et al. 2003), suggesting that the clouds that produce the broad emission components may be of the same origin as the associated absorbers.

### 4.2. Velocity Field

The narrow O vi line exhibits a systematic velocity shift from position A to position G by approximately 220 km s$^{-1}$. This gradient in the spatially resolved spectra explains why there are two narrow-line components in the integrated flux from the large-aperture FUSE spectrum, where it is unresolved. Crenshaw & Kraemer (2000a) reported a similar velocity pattern in their HST spectra. Das et al. (2006) successfully modeled this as a biconical outflow in which radial velocity changes as a function of the distance to the central nucleus; the emission-line knots show evidence for radial acceleration to a projected distance of $2''$ to the northeast, followed by deceleration up to $4''$. The O vi line widths also increase at $\pm 2''$ from the nucleus, probably implying a larger dispersion in these regions.

The broad component of O vi exhibits a qualitatively similar kinematic pattern, but at a larger amplitude: its centroid shifts by $\approx 1500$ km s$^{-1}$ (Fig. 10) across the same spatial region. Figure 11 shows similar trends for the narrow and broad components of C iv in the HST spectra which have not been explicitly noted in previous studies. The narrow component follows the kinematic pattern of the optical lines modeled by Das et al. (2006); the broad component of C iv shows behavior similar to that of O vi in the FUSE spectra. Prior observations that noted this blueshifted broad component invariably attributed it to the reflection of the BLR. The blueshift and width (at the position of the hot spot and in integrated light) are comparable to the broad polarized H$\beta$ line observed by Antonucci & Miller (1985).

In a scattered BLR picture, a blueshift is caused by the outflowing wind from the torus along our line of sight, and line width is due to the intrinsic broad-line width convolved with the thermal width of the hot reflecting wind. As a broad component is present in the FUSE spectra at all seven positions, it is possible to assume that this is reflected light from the hidden BLR. However, a large covering factor is needed to explain the observed fluxes. Assuming a covering factor of 0.1, the intrinsic flux of the broad O vi emission in NGC 1068 would exceed that in NGC 4151. A more reasonable explanation for the observed broad-line widths is the large velocity dispersion between bright knots. At approximately 2$''$ from the core (positions A and E), the FWHMs of broad components are the broadest at 3200 km s$^{-1}$. These maxima coincide with the widest splitting of velocity in bright knots (Crenshaw & Kraemer 2000a). With an intrinsic dispersion of $\approx 800$ km s$^{-1}$ and a separation in velocity of $\approx 2500$ km s$^{-1}$ between bright knots (from STIS results), data collected by the long FUSE slit would exhibit a broad component.
of \( \sim 3200 \text{ km s}^{-1} \), which is what we observe at positions A and E. Extended regions of hot, photoionized gas are seen in X-ray images of NGC 1068 (Young et al. 2001; Kinkhabwala et al. 2002) that could be visible manifestations of this hot outflow. It is natural to assume that these high-velocity clouds may be related to the associated absorbers (Crenshaw et al. 2003 and references therein) in AGNs, which are mostly blueshifted. As with the lower velocity, lower ionization emission-line gas, the acceleration of this high-ionization gas eventually is brought to a halt by an unknown deceleration mechanism, which might plausibly be interaction with the ambient ISM of NGC 1068. The evidence for deceleration at arcsecond scales may suggest that acceleration of the outflow materials may take place at subarcsecond scales.

4.3. \( \text{C}^{\text{iii}} \lambda 977 \)

The flux ratio of \( \text{C}^{\text{iii}} \lambda 1909 \) to \( \lambda 977 \) is extremely sensitive to temperature, and the value measured in NGC 1068 suggests a high temperature that is consistent with shock heating (Kriss et al. 1992). The \textit{FUSE} data taken with a large aperture (Table 3) reveal that this emission line consists of a narrow and a broad component. The broad component is weak and hence cannot be well separated in the data segments taken with a narrow \textit{FUSE} slit. The STIS data reveal that \( \text{C}^{\text{iii}} \lambda 1909 \) emission can be fitted with a narrow and a broad component of FWHM \( \sim 900 \) and 3500 km s\(^{-1}\), respectively. In principle, the ratio of \( \text{C}^{\text{iii}} \lambda 1909 \) to \( \lambda 977 \) should be calculated only between the narrow components. As shown in Figure 8, the flux of \( \text{C}^{\text{iii}} \lambda 977 \) is highly concentrated in positions C and D. High temperatures implied by this line emission may therefore be associated with the compact core. In a large portion of the ionization cone, the line ratios (\( \lambda 1909/\lambda 977 \)) are considerably higher, suggesting a lower temperature. However, the line ratios are considerably lower than those derived from the HUT data, where the broad \( \text{C}^{\text{iii}} \lambda 1909 \) component was included in the calculation.

4.4. \( \text{N}^{\text{iii}} \lambda 991 \)

The line ratio of \( \text{N}^{\text{iii}} \lambda 1750 \) to \( \lambda 991 \) is also temperature-dependent, and its value has been used to derive a high temperature in the ionization cone. The \textit{FUSE} data also reveal a pair...
5. SUMMARY

We have carried out high spectral resolution, spatially resolved spectroscopy of the nuclear region of the Seyfert 2 galaxy NGC 1068. The high spectral resolution of FUSE data enables us to study the line profiles of O vi, N ii, and C iii as a function of position across the nuclear region. Our observations using a long slit of 1.25″ × 20″ at steps of ~1″ along the axis of the emission-line cone result in a set of seven spatially resolved spectra running from ~2″ southwest of the nucleus to ~4″ northeast.

The O vi profiles exhibit considerable structure: a prominent broad component with FWHM ~3500 km s^{-1} and a narrow component of ~350 km s^{-1}. Both components show a position-dependent velocity gradient along the conical axis with a velocity shift of ~220 km s^{-1} in the narrow component and ~1500 km s^{-1} in the broad component. Both patterns are consistent with radial outflow from the nuclear region. Both the continuum and emission lines suggest low extinction; the UV continuum is flat to the shortest wavelengths in the FUSE spectrum, and the best fit is a power law with virtually no reddening. The He ii λ1640/λ1085 ratio also is reflective of a consistently low extinction factor across the emission-line cone. The majority of the C iii and N ii emission arises in the compact core, suggesting that the region with an extremely high temperature is very close to the nucleus and remains unresolved. The line emission at ~2″ northeast of the nucleus is strong and broad, characterized by (1) a strong Lyα flux but normal C iv flux, (2) a broad O vi line, and (3) a significantly enhanced C iii flux, possibly the result of hot knots associated with shock heating.

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