8-2000

The Narrow-Line Region in the Seyfert 2 Galaxy NGC 3393

Andrew J. Cooke  
*University of Edinburgh, UK*

J. A. Baldwin  
*Cerro Tololo Inter-American Observatory, Chile*

Gary J. Ferland  
*University of Kentucky, gary@uky.edu*

Hagai Netzer  
*Tel Aviv University, Israel*

Andrew S. Wilson  
*University of Maryland - College Park*

Click here to let us know how access to this document benefits you.

Follow this and additional works at: https://uknowledge.uky.edu/physastron_facpub

Part of the Astrophysics and Astronomy Commons, and the Physics Commons

Repository Citation

Cooke, Andrew J.; Baldwin, J. A.; Ferland, Gary J.; Netzer, Hagai; and Wilson, Andrew S., "The Narrow-Line Region in the Seyfert 2 Galaxy NGC 3393" (2000). *Physics and Astronomy Faculty Publications*. 143.

https://uknowledge.uky.edu/physastron_facpub/143

This Article is brought to you for free and open access by the Physics and Astronomy at UKnowledge. It has been accepted for inclusion in Physics and Astronomy Faculty Publications by an authorized administrator of UKnowledge. For more information, please contact UKnowledge@lsv.uky.edu.
THE NARROW-LINE REGION IN THE SEYFERT 2 GALAXY NGC 3393

Andrew J. Cooke1,2
Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK; andrew@intertrader.com

J. A. Baldwin
Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile3,4; baldwin@pa.msu.edu

G. J. Ferland
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40503; gary@cloud9.pa.uky.edu

Hagai Netzer
School of Physics and Astronomy, The Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel; netzer@wise.tau.ac.il

AND

Andrew S. Wilson
Department of Astronomy, University of Maryland, College Park, MD 20742; and Space Telescope Science Institute; wilson@astro.umd.edu

Received 1999 November 24; accepted 2000 March 7

ABSTRACT

The narrow-line region (NLR) of the Seyfert 2 galaxy NGC 3393 is dominated by a symmetric structure which appears as S-shaped arms in Hubble Space Telescope (HST) images. These arms, which occupy the central few arcseconds of the nucleus, border a linear, triple-lobed radio source. We use HST imaging and spectra, ground-based optical images, long-slit spectra, Fabry-Perot imaging spectroscopy, and VLA radio data to perform a detailed investigation of the kinematics and ionization of the line-emitting gas in NGC 3393 and of its relationship with the relativistic gas responsible for the radio emission. The excitation map [O III] 5007/([N II] 6548, 6584) shows a biconical structure, consistent with the anisotropic nuclear ionizing radiation expected in the unified scheme. Extrapolation to ionizing frequencies of our upper limit to the 2100 Å flux of the nuclear source provides a factor \( \geq 3 \times 10^4 \) too few ionizing photons to account for the recombination line emission, which also suggests that the nuclear ionizing source radiates anisotropically. However, the kinetic energy of the outflow is sufficient to power the line emission via photoionizing shocks, and a tentative detection of extended UV emission is consistent with this model. Furthermore, the broad component of the emission lines has a similar orientation and spatial extent as the triple radio source. Nevertheless, other tests are inconsistent with the photoionizing shock model—there is no correlation between local velocity dispersion, surface brightness, and excitation, and the gaseous abundances of [Ca II], [Al II], and Mg II are much lower than expected if these species have been liberated into the gas phase through grain destruction by shocks. We conclude that the radio lobes appear to have created denser regions of gas on their leading edges, thus forming the S-shaped arms, but that the ionization is most likely due to photoionization by an obscured central source.

Subject headings: galaxies: active — galaxies: individual (NGC 3393) — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

1.1. The Narrow-Line Region and the Unified Model

The geometry and ionization mechanism of the narrow emission line regions (NLRs) that are associated with most active galactic nuclei (AGNs) have been the principal focus of a number of detailed observational studies over the past several years. The general goal has been not only to try to determine on a galaxy-by-galaxy basis the spatial and kinematic layout of the NLR, but also to compare those results with the predictions of the "unified model" of AGNs.

The unified model supposes that all AGNs have basically the same structure, in which the field of ionizing radiation emitted by a central source is made anisotropic by the presence of some sort of obscuring torus and, in radio-loud objects, by beamed synchrotron emission (Antonucci 1993; Urry & Padovani 1995). The different observed types of AGNs are then caused mainly by different viewing angles. QSOs and Seyfert 1 galaxies are those AGNs which are viewed from within the solid angle subtended by a bicone of ionizing radiation, while Seyfert 2's are those viewed from outside the bicone. If there are no additional complications (the unified model does not describe the distribution of NLR gas), this predicts that the extended NLR in most or all Seyfert 2's should have the shape of two opposed cones, each with its apex at the active nucleus. The NLR structure in many Seyfert 2's can at least loosely be described in these terms (e.g., Pogge 1988; Wilson et al. 1993; Tadhunter & Tsvetanov 1989).

However, in some objects the spatial structure of the NLR is so closely associated with that of radio jets that the symmetry in the ionized volume may easily be due to processes other than just an anisotropic field of ionizing radia-
N. A. MUSSELMAN

SECTION 1

1. INTRODUCTION

NGC 3393 is a nearby (z = 0.0125), bright (m_B = 13.1; de Vaucouleurs et al. 1991) Seyfert 2 galaxy (also known as AM 1045-245, E501-G100) located on the outer fringes of the Hydra cluster. It is the only Seyfert 2 galaxy besides NGC 1068 that has emission lines sufficiently bright that a decent IUE spectrum could be obtained. It is an early type barred spiral (SBa(rs), with an “outer pseudo-ring,” according to de Vaucouleurs et al. 1991) Seyfert 2 galaxy (also known as NGC 3393) that has emission lines sufficiently bright that a detailed study of its NLR, which we describe in this paper.

1.2. NGC 3393

NGC 3393 is a nearby (z = 0.0125), bright (m_B = 13.1; de Vaucouleurs et al. 1991) Seyfert 2 galaxy (also known as AM 1045-245, E501-G100) located on the outer fringes of the Hydra cluster. It is the only Seyfert 2 galaxy besides NGC 1068 that has emission lines sufficiently bright that a decent IUE spectrum could be obtained. It is an early type barred spiral (SBa(rs), with an “outer pseudo-ring,” according to de Vaucouleurs et al. 1991) Seyfert 2 galaxy (also known as NGC 3393) that has emission lines sufficiently bright that a detailed study of its NLR, which we describe in this paper.

A pre-HST investigation of NGC 3393 was carried out by Diaz, Prieto, & Wamsteker (1988), who used a combination of optical and IUE spectra to study the integrated flux from the nuclear region. Using the low-resolution mode of IUE and its large aperture (20' x 10'), they detected a strong, flat UV continuum source (F$_\lambda$ $\approx$ 1.7 x 10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$) and a rich emission-line spectrum. Comparing the IUE measurement of He II $\lambda$1640 with a ground-based measurement of He II $\lambda$4686 taken through a 4' x 4' aperture, they deduced that there is essentially no reddening of the emission-line spectrum within NGC 3393. This is in spite of the fact that NGC 3393 is a “warm” IRAS source, indicating the presence of warm dust (Boisson & Durret 1986). The IUE data have been reextracted by Kinney et al. (1993), and additional observations have been reported in the infrared (Wang et al. 1991), and radio wavebands (Roy et al. 1994).

The new observations reported here include VLA radio mapping, ground-based optical narrowband images, long-slit and Fabry-Perot spectroscopy, and HST images and spectra.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Ground-Based Direct Images

Direct images in H_α + [N II] and the continuum at 6563 Å (rest wavelength 6482 Å) were obtained at the CTIO 0.9 m telescope on 1990 February 24. A Tektronix 512 x 512 CCD with 27 μm (0.45) pixels was used, in 1'6 seeing. Additional images in H_β, [O III] λ5007 and the continuum at 5257 Å (rest 5192 Å) were taken on 1992 April 9 using the f/13.5 focus of the CTIO 1.5 m telescope. A Tektronix 1024 x 1024 CCD with 24 μm (0.24) pixels was used in 1'8 FWHM seeing. These observations are summarized in Table 1.

The images were reduced in the normal manner using IRAF software, and co-aligned using field stars. Cosmic ray strikes were detected and removed when images for each filter were co-added. Some extra bias structure appeared in the H_β images. This was apparently constant along a row but changing along columns, and it was removed by subtracting the median of each row. The appropriate continuum image was then subtracted off each emission line image after scaling it so that the brighter stars would have the same number of counts in each image.

These images are used in the large-scale plots throughout this paper. They are analyzed in § 3.1.

2.2. Long-Slit Spectra

Grids of long-slit spectra were taken at the CTIO 4 m Blanco Telescope, using a GEC 385 x 576 CCD on the RC spectrograph (Table 2). A grating with 10 Å resolution (600 km s$^{-1}$ at 5000 Å) and wavelength coverage from 3700 - 6900 Å was used on 1990 March 2, while one giving 50 km s$^{-1}$ resolution over the wavelength range 4850-5140 Å was used on 1990 March 3. Both nights were photometric and the spectra were calibrated using standard stars from Stone & Baldwin (1983); LTT 2415, LTT 2511, and EG 274 on the first night, and Hiltner 600 and CD -32°9927 on the second night. Figure 1 shows the slit positions plotted over the l5257 continuum contours. The directions were chosen to align with the bimodal structure visible in the [O III] and H_β images (§ 3.1). The slit width was 1.5.

The data were reduced using standard IRAF software. Spectra were straightened to within approximately half a 0.73 pixel and rebinned to a uniform wavelength scale.

For the low-dispersion spectra, the sky was subtracted by using the average of regions approximately 1' to either side of the nuclear. Observations of line-free regions of the Seyfert galaxy NGC 4388, taken on the same night and with the same setup, were then scaled and subtracted to remove the stellar component as much as possible. Spectra of NGC 3393 could not be used for this purpose because the signal-to-noise ratio was too low in the line-free regions.

For both the low- and high-resolution data, emission line strengths and velocities were measured for various subsets of the spectra by fitting at each point a model consisting of a set of Gaussian line profiles at a single, fitted, redshift. The fitting process was automated to an extent, but the complexity of the model needed to be gradually increased to achieve good fits (i.e., the region near [O III] was fitted first and then the other stronger lines and finally spectral regions containing weak lines).

Errors in an individual parameter were calculated by varying that parameter, while keeping the fit as good as possible by adjusting other parameters, until the (unreduced) chi-squared statistic increased by 1.

At some positions only one line was strongly detected and so the line-ratio had a large error to one side of the best fit value (corresponding to an upper or lower limit). The points used in the analysis in § 3.4 are for those best-fit models in which at least one of the errors (upper or lower 1 σ bound) in log$_{10}$ ([O III] λλ4959, 5007/H_β) was less than 0.8.

<p>| TABLE 1 |
| FILTER |</p>
<table>
<thead>
<tr>
<th>TELESCOPE</th>
<th>CENTER λ</th>
<th>WIDTH (Å)</th>
<th>LINE</th>
<th>EXPOSURE (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 m .......</td>
<td>6649</td>
<td>76</td>
<td>Hα + [N II]</td>
<td>2 x 1200</td>
</tr>
<tr>
<td>0.9 m .......</td>
<td>6563</td>
<td>78</td>
<td>Continuum</td>
<td>2 x 1200</td>
</tr>
<tr>
<td>1.5 m .......</td>
<td>5257</td>
<td>44</td>
<td>Continuum</td>
<td>3 x 600</td>
</tr>
<tr>
<td>1.5 m .......</td>
<td>5081</td>
<td>44</td>
<td>[O III] λ5007</td>
<td>3 x 600</td>
</tr>
<tr>
<td>1.5 m .......</td>
<td>4905</td>
<td>44</td>
<td>H_β</td>
<td>2 x 600</td>
</tr>
</tbody>
</table>
A further set of 1.8 Å resolution long-slit data were taken on 1993 March 1, in just one position with the slit crossing the nucleus at P.A. 61°. These observations used the RC spectrograph on the CTIO 4 m telescope with four different grating setups to cover the wavelength range 3562-7562 Å. The detector was a thinned Tektronix 1024^2 CCD with 0.8 pixels.

The slit position was chosen to cut through the nucleus and the brightest parts of the two inner arms seen in the HST images described below (§ 2.4), crossing the nominal position of the HST spectra (§ 2.5). The slit width was 1.25. An arc lamp and a standard star were also observed at each grating setting. The data were wavelength and flux calibrated using the standard IRAF long-slit spectroscopy package and then a grid of one dimensional spectra was extracted from the two-dimensional images.

These spectra have 150–300 km s^{-1} resolution and (except for the bluest one) a continuum signal-to-noise ratio greater than 20:1 over the central parts of NGC 3393. An attempt was made to combine the four wavelength ranges using the galaxy’s continuum level. This was integrated over the whole slit length to normalize overlapping or adjacent portions of the different spectra. However, checks using the Hγ and [O III] λλ4959, 5007 emission lines, which appeared on overlapping portions of spectra taken with different setups, showed significant discrepancies between the same lines measured at the same nominal position. These differences are presumably a result of slight differences in the slit position, so we have analyzed the four grating setups as independent data sets.

These spectra are used mainly in §§ 3.3, 3.4, 4.4, and 4.5.

### 2.3. Imaging Fabry-Perot Data

The Rutgers Imaging Fabry-Perot Spectrometer was used on the Blanco 4 m Telescope on the night of 1995 February 2 to observe the [N II] λ6584 line complex. The “Narrow” etalon was used, giving 0.6 Å (27 km s^{-1}) FWHM resolution. The Tektronix 1024^2 CCD had a readout noise of 5 electrons rms, and 0.35 pixels. The seeing was 1.4 FWHM.

Single 2 minute exposures were made at each of 113 etalon/filter settings. The scanning order was to first make one pass through the spectrum from blue to red taking observations at every other etalon spacing and then to repeat with a second pass in the same direction filling in the intervening etalon spacings.

We observed the [N II] λλ6584, 6548 and Hα lines. However, because overlapping orders leaked through the

<table>
<thead>
<tr>
<th>Date</th>
<th>FWHM (Å)</th>
<th>λ Range (Å)</th>
<th>P.A. (deg)</th>
<th>Offset (arcsec)</th>
<th>Exposure (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990 Mar 2</td>
<td>10</td>
<td>3700–6900</td>
<td>10</td>
<td>0.0</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td></td>
<td>1.5</td>
<td>SE</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>SE</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>SE</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.0</td>
<td>SE</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.0</td>
<td>SE</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>NW</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>NW</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>NW</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.0</td>
<td>NW</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.0</td>
<td>NW</td>
<td>3 × 1200</td>
</tr>
<tr>
<td></td>
<td>74</td>
<td>1200</td>
<td>0.0</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>162</td>
<td>1200</td>
<td>0.0</td>
<td>1200</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>FWHM (Å)</th>
<th>λ Range (Å)</th>
<th>P.A. (deg)</th>
<th>Offset (arcsec)</th>
<th>Exposure (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990 Mar 3</td>
<td>0.8</td>
<td>4850–5140</td>
<td>44</td>
<td>0.0</td>
<td>8 × 1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>SE</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>SE</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>SE</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.0</td>
<td>SE</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.0</td>
<td>SE</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td>74</td>
<td>1200</td>
<td>0.0</td>
<td>8 × 300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>162</td>
<td>1200</td>
<td>0.0</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>162</td>
<td></td>
<td>34.0</td>
<td>NE</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>17.0</td>
<td>1200</td>
<td>17.0</td>
<td>NE</td>
<td>1200</td>
</tr>
<tr>
<td>1993 Mar 1</td>
<td>3.0</td>
<td>6186–7562</td>
<td>61</td>
<td>0.0</td>
<td>2 × 900</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4966–6333</td>
<td>0.0</td>
<td>2 × 900</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>4268–5130</td>
<td>0.0</td>
<td>2 × 600</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3562–4421</td>
<td>0.0</td>
<td>600</td>
</tr>
</tbody>
</table>
wings of some blocking filters, only a reduced wavelength range could be used. Our final cube, centered on $[\text{N II}] \lambda 6584$, spanned the wavelength range 6653–6676 Å with 54 images. There appears still to be some leakage into the blueward part of the wavelength range retained. The two sweep observing schedule led to a gap of 2 hr between the two sequences of exposures.

A neon comparison lamp was observed at intervals of about once per hour (i.e., before, after, and five times during the observations). This showed typical wavelength drifts of less than 0.1 Å (with two exceptional changes of 0.2 Å), which were removed by linear interpolation between comparison observations. The telescope was refocused twice during the observing sequence.

The data were corrected for spatial drifts and transmission differences using measurements of three bright stars in the images and then combined into a cube using the IRAF package “Fabry” (available from CTIO).

These data are used to constrain the general orientation of the galaxy in § 3.2 and to explore the kinematics of the central region in § 4.4.2.

2.4. HST Direct Images

In order to study the nuclear region at much higher spatial resolution, Hubble Space Telescope direct images were taken with the pre-COSTAR Planetary Camera, on 1993 June 7/8. The pixel size is 0′′.043. Table 3 summarizes the filters and exposure times.

The images were recalibrated using the calibration files recommended by, and available from (early 1995), STEIS. Emission line images were combined (no alignment was necessary), rejecting bad pixels. The single continuum image was median filtered to remove cosmic ray strikes (the peak in this band was sufficiently smooth for it to retain its shape under mild filtering).

The images were deconvolved using both the Maximum Entropy and Lucy algorithms. Results from the two algorithms were similar. Since an implementation of MemSys by Dave Robinson (UK HST Support Facility) was the

<table>
<thead>
<tr>
<th>Filter</th>
<th>Center $\lambda$ (Å)</th>
<th>Line</th>
<th>Exposure (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f664n</td>
<td>6640</td>
<td>Hα + $[\text{N II}]$</td>
<td>1100 &amp; 2 × 1900</td>
</tr>
<tr>
<td>f547m</td>
<td>5470</td>
<td>Continuum</td>
<td>1 × 600</td>
</tr>
<tr>
<td>f502n</td>
<td>5020</td>
<td>$[\text{O III}]$ λ4959</td>
<td>1100 &amp; 5 × 2000</td>
</tr>
<tr>
<td>f606w</td>
<td>6060</td>
<td>Cont. + Hα + $[\text{N II}]$</td>
<td>1 × 500</td>
</tr>
</tbody>
</table>
The continuum was then subtracted from each line (plus continuum) image. Because there were no reference stars on the images, the intensity scale factor for the continuum image was determined by subtracting as much continuum as possible without producing a negative signal level in the parts of the difference image where there were no strong emission lines.


Finally, we also used two archival HST images. The first was taken with the WFPC2 for M. Malkan and collaborators. The F606W filter was used, which includes the Hα, [N II] emission lines and approximately 1500 Å of continuum blueward of these lines. We used a 3 × 3 median filter to remove most of the cosmic ray events. This image goes considerably deeper than the others and is very valuable for looking at faint emission and dust absorption features outside of the immediate nuclear region. It has also been shown by Pogge (1997) and by Malkan, Gorjian, & Tam (1998). We also used a FOC image taken for T. Heckman to place an upper limit on the ultraviolet continuum flux. This was a 1962 s exposure through the F210M filter. We used the standard calibration and determined the upper limit by

The continuum was then subtracted from each line (plus continuum) image. Because there were no reference stars on the images, the intensity scale factor for the continuum image was determined by subtracting as much continuum as possible without producing a negative signal level in the parts of the difference image where there were no strong emission lines.

The images were used throughout §4.

2.5. HST Spectra

The HST Faint Object Spectrograph (FOS) was used on 1993 November 16 with the intention of obtaining ~ 500 km s\(^{-1}\) resolution spectra of a bright knot (§ 4.5.3) 1.8 NE of the nucleus. The wavelength range 1150–6817 Å was covered using five gratings (Table 4). The data were reduced in 1996 using the AIPS flux calibration method, smoothed with a 5 pixel (1.25 diode) boxcar, and then co-added. They are analyzed further in § 4.5.3.

2.6. VLA Radio Maps

The VLA was used to map NGC 3393 on 1990 October 27 (C configuration, 3 hr total time), 1991 October 11 (BnA configuration, 6 hr) and 1992 November 29 (A configuration, 6 hr). On each date observations were made at 1.4 GHz (L band), 5 GHz (C band) and 8.4 GHz (X band). The source 3C 286 was used as a primary flux calibrator. Sources 1055–242 (C band) and 1034–293 (L and X bands) were used as phase and amplitude calibrators.

The data were reduced using standard AIPS programs. The images were cleaned and self-calibrated. They are analyzed further in § 4.3.

3. THE OUTER REGION

3.1. General Morphology

Figure 2 shows contour plots of the central 2′ of the ground-based [O III], Hα and λ6563 continuum images (the full images are 200′′ × 200′′), and also blow-ups of the nuclear region. The axes are labeled in arcseconds relative to the central nucleus. North is up and east to the left.

The continuum images show a roughly oval bar in P.A. 156°, extending to a radius of ~ 19′′ (3.4 h\(^{-1}\) kpc projected on the sky). They also show weak outer ringlike segments, which the Hα image shows to be tightly wound spiral arms, containing many giant H II regions and connecting onto the ends of the stellar bar. These arms can also be seen on the Digital Sky Survey image.

Both the de Vaucouleurs et al. (1991) and Lauberts & Valentijn (1989) catalogs list the major to minor axis ratio as 1.09, and the latter reference also gives a major-axis position angle of 137°. However, our continuum images and the Digital Sky Survey show that the outer contours are determined by the shape of the spiral arms. A plateau of weak stellar continuum fills the region between the spiral arms and the stellar bar. This brighter area is elongated along P.A. ~ 45° with about the above-quoted major to minor axis ratio. However, the elongation appears to be the result of the NW side being truncated because of the details of the spiral structure rather than, as was suggested by Buta (1995), being the projection of circular outer isophotes. Whatever the morphology of the central structure, it is clear that the galaxy is viewed nearly face-on.

The continuum images show only very modest amounts of dust. However, the previously mentioned HST F606W image (see Figure 2, below) does show several small dust lanes superimposed on the bar, including one which seems to trail off the emission-line feature described below in § 4.2 as the “outer SW arm” and then cross a much more prominent dust lane which cuts across the end of the stellar bar 11° SE of the nucleus.

The ground-based emission-line images (Fig. 2) show that the strongest emission from high-ionization gas comes from bright knots symmetrically placed ~ 1.5′ to either side of the nucleus in P.A. 55°. There is also an extensive, contiguous area of [O III] emission forming an elongated feature which extends ~ 15′′ on either side of the nucleus in P.A. 44°, at ~ 68° to the stellar bar. These same features can be seen in the Hβ (not shown) and Hα images.

3.2. Orientation and Kinematics

Figure 3 shows a velocity map of the Fabry-Perot [N II] λ6584 data, made using an automatic fitting routine kindly provided by R. Schommer. At each spatial location this program fits the data with a single Gaussian line profile plus a constant continuum, with the width, peak intensity and velocity of the line, and the continuum level as the variable parameters. The data were fitted with no spatial binning in the bright central area of the emission region, but with 3 × 3 and 5 × 5 binning in the outer, faint regions. The range of measured [N II] velocities is in good agreement with the long-slit spectroscopy data (§ 2.2).

Most of the H II regions in the outer spiral arms that are visible in Figure 2 also appear in the velocity map. There is
a skew between the velocity field of the inner regions including the bar, and that of the outer arms. Here we fitted a rotation curve to the data outside 23'' radius from the nucleus in order to determine the orientation of the galaxy as a whole. The inner region is discussed in detail in § 4.4.2.

Rather than using the Gaussian fits on which Figure 3 is based, we fitted a kinematic model directly to the Fabry-Perot data cube, using the ground-based Hα and continuum images to constrain the spatial structure. This procedure is extended in § 4.4.2, where we take advantage of

Fig. 2.—Ground-based images. The right-hand plots show the central regions. Axes are labeled in arcsec from the peak of the continuum emission. Contours have logarithmic spacings corresponding to factors of 1.6, with the highest contour a factor 1.6 below the peak intensity at the nucleus in each passband. The lower limits of the contours are set at about 3σs, above the sky level on each plot, with values relative to the peak of (a) 5.4 × 10⁻⁴, (b) 1.4 × 10⁻³, (c) 3.4 × 10⁻⁴, (d) 3.6 × 10⁻³, (e) 3.4 × 10⁻⁴, and (f) 3.6 × 10⁻³.
the high spatial resolution in the HST images to constrain the central velocity field.

We fitted a rotation curve of the form (Bertola et al. 1991)

\[ v_1(r) = V_{sys} + \frac{A r}{(r^2 + C^2)^{p/2}}. \]

The results were \( V_{sys} = 3750 \pm 3 \) km s\(^{-1}\) (heliocentric), \( A = 510 \pm 2 \) km s\(^{-1}\) arcsec\(^{-0.012}\), \( C = 17^\circ\), \( p = 1.012 \pm 0.002\), \( i = 13^\circ \pm 1^\circ\), and \( \phi_0 = 68^\circ \pm 4^\circ\), where \( i\) is the inclination to the line of sight and \( \phi_0\) the line of nodes as defined by van der Kruit & Allen (1978). The fitted FWHM of the emission lines was \( 32 \pm 3 \) km s\(^{-1}\), essentially the instrumental resolution. The errors in \( C\) are large and uncertain, since this parameter would normally be determined from data at small radii which are excluded from this fit. The values of \( i\) and \( A\) are strongly anticorrelated and sensitive to the quality of the model fitted. Systematic errors in these parameters may be much larger than the random errors quoted above.

Thus, the major axis runs NE-SW with gas in the SW disk moving toward us while gas to the NE is receding. Assuming the spiral arms trail, the galaxy is then rotating counterclockwise on the sky with the near side of the disk to the NW and the far side to the SE.

The fitted kinematic center is \( 1.2'\) N of our estimate of the position of the nucleus from comparing the Fabry-Perot continuum-intensity map to the HST images. The discrepancy in positions is probably not significant since the fit was for the usual idealized model of circular velocities in a plane and used only the outermost region of the galaxy.

The best-fit value of \( i\) shows that the parent galaxy has an inclination of about \( 13^\circ\) to the line of sight. This means that some information can be obtained about gas motions in the plane of the galaxy.

### 3.3. Reddening

The nine central low-resolution spectra at P.A. 44° were co-added in order to get the highest possible signal to noise ratio. Figure 4 shows the H\(\alpha\)/H\(\beta\) ratio from these data, marked over the \( \lambda5257\) continuum contours. The unobscured (minimum) value of \( \log_{10} (H\alpha/H\beta) \) should be approximately 0.5 (assuming Baker-Menzel case B). A larger value indicates that the emission is reddened. Both of the more distant regions to the NE and SW appear to be reddened, with \( I(H\alpha)/I(H\beta) \sim 20\) [corresponding to \( E(B-V) \sim 1.8\)], but there is little evidence for reddening at the nucleus. The FOS spectra confirm the low reddening in the central region (§4.5.3).

Therefore, we will correct only for Galactic reddening throughout the remainder of the paper. We use \( E(B-V) = 0.06\) from the Burstein & Heiles (1982) maps, and the form of the reddening law given by Cardelli, Clayton, & Mathis (1989), with \( R_V = 3.1\).
3.4. Ionization Structure

To develop a two-dimensional picture of the ionization structure, the nine central low-resolution spectra at P.A. 44° were co-added in groups of three. Simple models were then fitted to these and the remaining (lower signal-to-noise) spectra. The variable parameters were: the intensities of the Hα, Hβ, [O III] λ4959 and λ5007, [N II] λ6548 and λ6584 lines; the redshift; the line width; and the continuum levels.

This allowed two reddening-free ionization diagnostics to be measured. These are the [O III]/Hβ and [N II]/Hα intensity ratios, which are plotted against each other in Figure 5. The solid line shows the division between H II regions and AGNs, taken from Veilleux & Osterbrock (1987) and Baldwin, Phillips, & Terlevich (1981), but modified for measurements of the total fluxes in the [O III] and [N II] doublets. H II regions are plotted as filled circles, while measurements in the power-law photoionization/shock-heating region are shown as gray diamonds which become lighter as the distance from the dividing line increases.

The symbols retain the same meaning in Figure 6, which plots the data over the (Hα + [N II]) image. The ionizing flux in the NE section of the outer spiral arm is dominated by starlight. Figure 4 suggests that the spectra from this region are significantly reddened, although underlying stellar absorption of Hβ might also be a factor. The gas in the spiral arm on the SW side of the galaxy is also ionized by stellar radiation, and reddening again appears to be present (although not as strongly as in the NE).

The ionizing flux in the regions closer to the nucleus is dominated by an AGN component. This result is confirmed by an additional ionization diagnostic, the ([S II] λ6716 + λ6731)/Hα intensity ratio, measured from the same co-added spectra used for Figure 4.

The extent of the high-ionization gas is shown better in Figure 7, which plots the [O III]/Hβ intensity ratio measured from the high-dispersion spectra. Even though we do not have good coverage in the regions of the galaxy away from the P.A. ~ 44° axis, it is clear that the highest ionization gas is confined to the elongated [O III]-bright structure in P.A. 44°.

Figure 8 shows the combined results from the long-slit spectra, with the higher ionization gas marked by circles. The middle section shows the spatial arrangement of points. Above is a diagram showing the distribution of FWHM line widths, below is the distribution of [O III]/Hβ line strengths. The horizontal position of the points is the same in the different panels. Circles represent the gas ionized by power-law sources, while stars represent low-ionization gas. The broadest power-law ionized lines are marked with white circles while the rest are either gray or black, showing regions which appear to be spatially separate. It is clear that the broadest lines tend to be close to the nucleus.
There is a region to the NE (Fig. 8, leftmost gray region) that is separate from the core and can be identified with the bright patch of [O III] emission seen in Figure 2 at ~20° E, 20° N of the nucleus. This could be some kind of bow shock like that seen in NGC 3516 (Miyaji, Wilson, & Perez-Fournon 1992). Alternatively, it may be an inner region of the spiral arm visible in the Hα image (Fig. 2) that has been ionized by radiation from the central region.

4. THE CENTRAL REGION

4.1. Continuum Morphology

A contour map of the HST deconvolved continuum image (at 5470 Å) is shown in Figure 9. The data are noisy, but a dust lane can be seen cutting into the central 0°.5 of the continuum peak from both P.A. 115° and, on the opposite side, P.A. 295°. This is more easily seen on an image display. Pogge (1997) has also remarked on this dust lane in his study of the HST archival image through the F606W filter. Because of the distortion from this feature, we cannot accurately measure the radial profile of the nuclear bulge.

Nevertheless, there appears to be a central “spike” on the continuum source which is significantly narrower than the central continuum peak in typical nonactive galaxies and Seyfert 2’s. Nelson et al. (1996) have fitted Gaussians to the central region of HST WFPC1 images of a nearly complete sample of Seyfert galaxies. Following their prescription for Seyfert 2’s, we find a FWHM for the spike of 5.3 pixels. Comparison with Figure 5 of Nelson et al. shows that, after taking the redshift into account, the width of the core in NGC 3393 is 3–4 times smaller than in most Seyfert 2’s or in their model of a typical nonactive spiral galaxy. However, it is 2–3 times broader than the nuclei of Seyfert 1’s, which were almost always unresolved with HST.

4.2. The S-Shaped Emission-Line Regions

The HST emission-line images are shown in Figures 10 and 11 after being deconvolved and continuum-subtracted.

An S-shaped region of high-excitation gas straddles the nucleus, with approximately symmetrical curved arms which leave the nucleus at P.A. 90° and 270° before, at a radius of 1′.5 (270 pc), curving sharply round toward smaller position angles (the sense of curvature is the same as the large-scale spiral arms). In the NE arm the brightest regions are concentrated to the inner edge of the arm. The SW arm has an inward extension back toward the nucleus, after the initial curve, which may be some sort of loop or bubble; we will call this the “SW loop.”

In addition, there is a much fainter armlike structure about three times farther out on the SW side, extending...
from ~2"3 S, 3"7 W to ~4"5 S, 1"5 W of the nucleus. This can be seen most clearly in the F606W image (Fig. 12), but it is also visible in both the [O III] and Hα images (especially on an image display), showing that the feature is due to line emission. The shape of this outer feature is similar to that of the brighter SW arm: it is an arc with the nucleus roughly at its center of curvature, and with an inward extension in about the middle of the visible segment.

There are two adjacent emission knots at the center of the S-shaped pattern. The northern one lies almost exactly along the line of symmetry joining the two arms and is coincident with the peak in the continuum image. We have therefore taken this position to define the nucleus. The southern knot is located 0"27 from this at P.A. 195°. The nucleus is brighter than the southern knot on the Hα image, but the opposite is true on the [O III] image; this may be due to different excitation, different reddening, or both.

Table 5 shows the relative contributions of the various emission-line regions visible on these images, as a fraction of the total emission within 3" radius of the nucleus for each continuum-subtracted image. The bright S-shaped arms, excluding the region within 0"6 radius of the nucleus, contain roughly half the [O III] and Hα + [N II] flux, and 10%-15% comes from a diffuse source approximately centered on the nucleus. Most of the rest comes from fainter areas at radii larger than the brightest part of the arms, but which appear on the images to be part of the arms. The nucleus, the southern knot, and the SW loop contribute only 1%-2% each if integrated over 0"6 diameter apertures as would be appropriate for point sources. Table 5 also lists a relative flux for the outer SW arm, which lies outside the 3" fiducial radius.

The relative fluxes in Table 5 were put onto the same absolute scale as our ground-based measurements by summing the [O III] λ4959 and (Hα + [N II]) fluxes from the grid of low-resolution P.A. 44° long-slit spectra over a 7"5 × 12"4 rectangular area centered on the nucleus and

<table>
<thead>
<tr>
<th>Region</th>
<th>[O III]a</th>
<th>Hα + [N II]b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total r ≤ 3&quot;</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Arms</td>
<td>0.44</td>
<td>0.42</td>
</tr>
<tr>
<td>Nucleus, 0&quot;6 dia. ap.</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Southern knot, 0&quot;6 dia. ap.</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>SW Loop, 0&quot;6 dia. ap.</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Diffuse, r ≤ 0&quot;6</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>Diffuse, r ≤ 1&quot;0</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Diffuse, r ≤ 3&quot;0</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>Outer SW arm</td>
<td>0.10</td>
<td>0.08</td>
</tr>
</tbody>
</table>

a Normalized to 4.4 × 10⁻¹³ ergs cm⁻² s⁻¹.
b Normalized to 1.1 × 10⁻¹² ergs cm⁻² s⁻¹.
Fig. 7.—Logarithm of $[\text{O} \text{ III}]/\text{H} \beta$ line ratios, superimposed on $[\text{O} \text{ III}]$ contours

4.3. Optical–Radio Alignment

Figure 13 shows the 8.4 GHz radio map, which shows three emission regions extending along an axis at P.A. 56°. A polarization intensity map shows no appreciable structure above a noise level of 100 $\mu$Jy beam$^{-1}$. The power-law exponent of the spectrum of the radio continuum emission ($f \propto v^{-\alpha}$), calculated by comparing the images at 8.4 and 5 GHz (the two maps with highest spatial resolution), averages $\alpha = 1.2$, 0.6, and 1.1 in the NE, central, and SW lobes, respectively. The 5 and 1.4 GHz maps do not show any additional, larger scale emission. The coordinates of the central source are (1950B) $\alpha = 10^h45^m59^s458$, $\delta = -24^\circ53'51"44$.

The central source is unresolved and has a significantly flatter spectrum than do the two lobes. Both this and the three-component structure are very typical of Seyfert 2 galaxies, where the central source is usually identified with the optical nucleus. However, to align the radio and $HST$ nuclei requires a shift of $\sim 2'5$ to the west (for the optical data) according to the $HST$ and VLA pointing information. The VLA positional errors should be negligible, while the $HST$ errors are usually less than 1". Some telescope “jitter” was noted during the $HST$ observations and if, instead of the nominal $HST$ coordinates for the nucleus, we use new ones derived from the GASP coordinates for a bright star at the edge of the $HST$ image, the discrepancy is cut to 1"2.

After this shifting to align the (apparently) central sources, the $[\text{O} \text{ III}]$ and radio images superpose as shown in Figure 13. The SW radio lobe is slightly resolved ($\sim 0'07$ FWHM) and falls on top of the SW loop. The NE lobe is dimmer and more extended; the CLEAN algorithm modeled it as three point sources spaced about $0'3$ apart (see Fig. 16, below, where these three point sources are called A, B, and C). It does not coincide with any prominent $[\text{O} \text{ III}]$ region, but rather lies inside the NE arm. The situation does not change qualitatively if we instead align the central radio source with the southern knot (a shift of $0'3$ to the south); the NE radio source still falls in the center of the arc of the NE arm and the SW radio lobe still falls on the SW loop.

4.4. Velocity Field

4.4.1. $[\text{O} \text{ III}]$ Profiles

The emission-line profiles can be studied at good signal to noise using the high-resolution long-slit spectra. Line widths from these data were presented earlier (Fig. 8).
Figure 14 shows how the [O III] 5007 profiles change across the central region of the galaxy. Each profile is separately scaled in intensity and covers the velocity range $\pm 600$ km s$^{-1}$ with a vertical line marking the systemic velocity. The data have been summed over the number of columns corresponding to the area covered by the plot.

From the NE to the SW, the strong emission lines show a sudden change in redshift at the nucleus. Disregarding cosmic ray strikes (easily recognized by their extremely narrow widths) there is no clear example of multipeaked emission. However, there is a clear pattern of asymmetries. To the NE, where the peaks are redshifted, the profiles show a blueward-slanting asymmetry. To the SW, where the peaks are blueshifted, the profiles show a redward-slanting asymmetry. Very similar switches in the sense of line asymmetry across the nucleus are seen in other Seyfert 2 galaxies, such as 0714—2914 (Wilson & Baldwin 1989) and Mrk 1066 (Bower et al. 1995).

The nature of these profiles can be seen better in Figure 15, which shows a portion of a high-resolution spectrum from the slit position cutting across the nucleus at P.A. 44°. At the nucleus and on the SW side there is clearly a two-component structure that can be interpreted as a narrow peak set on a broad (FWHM $\sim 1000$ km s$^{-1}$) base which, relative to the narrow peak, is blueshifted at the nucleus but redshifted in the SW. The two-component structure is less obvious to the NE side, but there is both a modest blueward asymmetry and a weak red tail, with FWZI $\sim 1000$ km s$^{-1}$.

Comparison of Figures 14 and 15 suggests that the asymmetries can be modeled by a combination of broad and narrow components each with their own velocity structures.

4.4.2. Fabry-Perot Imaging Spectroscopy

The best information on the two-dimensional velocity field of the central region comes from the Fabry-Perot [N II] $\lambda 6584$ data. However, these data have some prob-
lems: (1) their limited velocity coverage (1035 km s$^{-1}$) and leakage from other orders will tend to cause the broad component to be mistaken for continuum radiation; and (2) they were taken in rather poor seeing (1.4 FWHM). To compensate for these, we used our direct images to constrain the continuum level and the spatial structure of the emission line regions. The direct images were combined with a model velocity field and convolved to the measured Fabry-Perot spatial resolution to produce a model Fabry-Perot data cube, which was then compared to the observed data cube.

In the central region (including the S-shaped arms and SW extension) the line intensity was calculated by convolving the $HST$ Hα + [N II] image with a suitable PSF. Elsewhere the line intensity was constrained by the ground-based Hα + [N II] image. Each of these images had a separate, fitted, scale factor. The exact (fraction of a pixel) position of the $HST$ data relative to the ground-based images was also fitted. The continuum, throughout the model, was the ground-based image (Fig. 2).

The general velocity field of the narrow component can be judged from Figure 3, which was made by fitting a single Gaussian velocity profile plus a continuum level at each Fabry-Perot spatial pixel; the broad component will generally be fitted as continuum, and so only the narrow component is measured. Since the extended zone of [O III] emission (along the radio axis) shows roughly parallel contours in the velocity field map, we chose solid body rotation as a simple model for the narrow line component. The variable parameters for the narrow component's velocity field are the mean recession velocity, orientation, rate of rotation, and a line width which was assumed to be constant across the emission region.

The form of the velocity map for the broad line component was chosen by trial and error. We finally divided NGC 3393 into four separate areas: the region including and interior to the S-shaped arms was split into three parallel NW-SE bands, one covering the nucleus and one covering each arm, and an additional "surroundings" region was specified to allow for the possibility of a broad component outside the S-shaped arms. An independent velocity and line width was fitted for each of these four areas (i.e., eight free parameters).

At each iteration step, the fitting process first generated separately for the broad and narrow components a succession of models which were used to obtain a best fit for the velocity field parameters for each component. In this process, the free parameters were varied to minimize the M-estimate $| (data - model) / error |$. This is similar to least squares fitting but assumes a wider distribution of outliers.
since the data contain cosmic-ray strikes (Press et al. 1992). In one dimension, with constant errors, it is equivalent to finding the median, rather than the mean. The expected error at each pixel was calculated from the readout noise and gain, assuming photon counting statistics, with appropriate corrections for the calibrations described in §2.3. The resulting model for each component was then convolved to the Fabry-Perot data resolution.

The relative strengths of the broad and narrow components in each pixel were then adjusted to minimize $\chi^2$ in the fit to the spectrum at that spatial point. This produced the two input models for the next iteration step. This two-stage procedure was necessary for computational speed (a more exact approach, which would have involved combining the data at the HST resolution, required too much time). Since the relative strengths of the two components (broad and narrow) are fitted at each spatial position, a cosmic ray strike will only affect a small subset of the model—the global fit was still assessed using the more robust M-estimate.

The final result after approximately 2000 iterations is a model in which the total flux from the broad and narrow components together is consistent (in the central regions) with the HST images at the full HST resolution, while the division of the flux between the two components is consistent with the Fabry-Perot spectra at their lower spatial resolution.

Error estimates for the various parameters were calculated by splitting the cube into two separate data sets and fitting the model to each. The variation in the results, after correcting for the increased scatter expected from a reduced data set, gave a simple estimate for the expected errors in each parameter.

The velocity field of the narrow component was fitted by solid-body rotation with a velocity gradient of $32 \pm 0.5$ km s$^{-1}$ arcsec$^{-1}$ (180 $h$ km s$^{-1}$ kpc$^{-1}$), inclination $i = 21^\circ \pm 2^\circ$ and line of nodes $\phi_0 = 37^\circ \pm 3^\circ$. This axis is $12^\circ$ (in three dimensions) from the axis of rotation of the outer galaxy (§3.2). Taking into account that some of this difference may be due to systematic errors in the fit to the (faint) outer emission (§3.2), the shift is still significant. The fitted value for the (constant) FWHM of the narrow component is $194 \pm 5$ km s$^{-1}$. The gas at the position defined by the kinematics of the outer galaxy to be the center of rotation has a recession velocity $20 \pm 2$ km s$^{-1}$ higher than the systemic velocity found from the outer galaxy. The peculiar velocity and widths for the broad component are given in Table 6. All the line widths are significantly larger than for the gas following solid body rotation.

The spatial distribution of the intensities of the two line components is shown in Figure 16. The broad component has two peaks in intensity—one fairly central, within the arms region, and one aligned with the southern side of the NE arm. The narrow component has two peaks which are
aligned with the outermost arcs of the S-shaped arms; it is also more extended than the broad component, with significant emission in the region of extended emission to the SW.

The exact spatial structure of the broad component is affected by the mask used to delineate the various regions. However, for all choices of mask the model indicated that broad components with the widths of those seen in Figures 14 and 15 do not extend beyond the S-shaped arms but do fall on the NE arm and in the area interior to the arms, while the narrow component comes most strongly from the S-shaped arms but also from the outer SW arm and other regions outside the arms. These general results are also confirmed by just fitting simple single-Gaussian plus continuum models at each spatial pixel in the Fabry-Perot data, so we consider them to be very robust.

4.4.3. The High-Resolution Long-Slit Spectra

We now return to the results from the higher spectral resolution long-slit spectra which provide an additional two-dimensional map of the narrow and broad components. Although their spatial resolution is low (1.5 slit width × 0.7–0.8 pixel−1), they cover the full velocity profile of the broad component, thus giving a more reliable measure of its width and velocity.

Two components were fitted with Gaussian profiles at each pixel along the slit in the grid of 0.8 Å resolution spectra at P.A. 44° and the single 1.8 Å resolution spectrum covering Hα at P.A. 61°. The velocities and line widths for these two independent data sets were identical to within expected errors (from both limited data and slightly different spatial positions). The Hα fluxes, velocities, and widths for the P.A. 61° data are shown in the top three panels of Figure 17, with the broad component shown as a very broad gray line and the narrow component as a thick dark line. The velocity and width were measured by simultaneously fitting the Hα, [N II], and [S II] lines.

The same panels show as filled circles the results of a single-component Gaussian fit to the same data, at every 0.8 pixel in the central regions and summing over three...
pixels in the fainter outer regions. Here the flux is again for Hα, but the width and velocity are measured from just the [S II] lines. All of the line widths have been corrected for the instrumental resolution. We attempted to make similar measurements of the two components of Hβ and [O III] using the P.A. 61° spectrum covering that wavelength range. However, the results were inconsistent with the P.A. 44° results for the same lines, presumably because of slight differences in the slit positions. We use these data only to measure the relative intensities of the [O III] lines (§ 4.5.2).

The top panel in Figure 17 also shows the flux from a 1″ wide section at P.A. 61° through the HST [O III] image (thin dark line). The fluxes from the long-slit and HST data have each been scaled arbitrarily, but the correct ratio of narrow and broad component fluxes is shown. The vertical dashed lines show the approximate locations of the peaks of the radio emission in the two lobes.

The second panel from the top includes a thin horizontal line indicating the width fitted to the Fabry-Perot data for the narrow component. We do not show the Fabry-Perot results for the broad component widths because we do not think that they are reliable.

Figure 17c again includes the Fabry-Perot results. The solid body model fitted to the component gives the velocity gradient shown by the thin diagonal line, while the velocity of the broad components in the two arms are shown with two short horizontal lines. The velocity of the central broad component (−258 km s⁻¹) is off scale.

The remaining three panels (Figs. 17d, 17e, and 17f) will be discussed in § 4.5.2.

The P.A. 61° Hα, [N II], and [S II] data gave width and velocity results consistent with the P.A. 44° data, and in addition the two-dimensional structure of the narrow and broad components derived from the P.A. 44° grid agrees, within the limits of the lower resolution, with the results from the Fabry-Perot analysis. In particular, the long-slit data show that the broad component is concentrated within 2″ of the nucleus, in agreement with the Fabry-Perot results (Fig. 16); the apparent extension of the thick gray line in Figure 17 beyond this radius probably reflects smearing by seeing and instrumental resolution. We therefore believe that the kinematic and spatial structures of the two velocity components have been measured reliably.

### 4.5. Physical Conditions

#### 4.5.1. Average Parameters from the Low-Resolution Spectra

Table 7 shows a fit to the low-resolution spectra, co-added over a 8″ × 8″ region centered on the nucleus. While this includes lines at different redshifts, making the measured line width artificially large, the gas appears, from Figure 6, to be at uniformly high ionization. The Hα, [N II]...
FIG. 13.—Cleaned map made from the combined 8.4 GHz observations (all baselines), superimposed on the HST [O III] image after shifting as described in text. Successive contours are logarithmic, separated by a factor of 2, and the peak intensity is 7.08 mJy beam~1. The small oval in the lower right corner is the beam profile at half-maximum intensity.

TABLE 7
THE MODEL FITTED TO THE GROUND-BASED LOW-RESOLUTION SPECTRA

<table>
<thead>
<tr>
<th>LINE</th>
<th>WAVELENGTH (Å)</th>
<th>FLUX</th>
<th>OBSERVED</th>
<th>CORRECTED *</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O III]</td>
<td>3726, 3729</td>
<td>155 ± 5</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>[Ne III]</td>
<td>3869</td>
<td>77 ± 7</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>Hδ</td>
<td>3967</td>
<td>31 ± 5</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Hγ</td>
<td>4101</td>
<td>15 ± 4</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>[O III]</td>
<td>4341</td>
<td>37 ± 5</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>[O III]</td>
<td>4364</td>
<td>10 ± 4</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>[N II]</td>
<td>4686</td>
<td>29 ± 3</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Hβ</td>
<td>4861</td>
<td>100 ± 3</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>[O III]</td>
<td>4959</td>
<td>341 ± 5</td>
<td>339</td>
<td></td>
</tr>
<tr>
<td>[N II]</td>
<td>5007</td>
<td>1030 ± 10</td>
<td>1022</td>
<td></td>
</tr>
<tr>
<td>[O I]</td>
<td>5199</td>
<td>13 ± 3</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>[O I]</td>
<td>6360</td>
<td>34 ± 3</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>[O I]</td>
<td>6364</td>
<td>10 ± 2</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>[N II]</td>
<td>6548, 6584</td>
<td>492 ± 15</td>
<td>463</td>
<td></td>
</tr>
<tr>
<td>Hz</td>
<td>6563</td>
<td>359 ± 13</td>
<td>338</td>
<td></td>
</tr>
<tr>
<td>[S II]</td>
<td>6716, 6731</td>
<td>202 ± 5</td>
<td>189</td>
<td></td>
</tr>
</tbody>
</table>

Redshift z | 0.01315
FWHM (km s~1) | 336 ± 10 – 20

* Corrected for Galactic reddening.

blend was fitted by requiring the [N II] doublet ratio to be 3:1.

It was not possible to meaningfully separate the [S II] λ6716, 6731 doublet in order to derive a density from these data, but the following section shows that the densities are moderate. The reddening-corrected [O III] ratio is \( I(\text{[OIII]})_{\lambda4959 + \lambda5007}/I(\text{[OIII]})_{\lambda4363} = 140 \pm 50 \), corresponding at the low-density limit to a temperature \( T_e = 1.1 \pm 0.2 \times 10^4 \) K. The [N II] \( I(\text{[NII]})_{\lambda6548 + \lambda6584}/I(\text{[NII]})_{\lambda5755} \) ratio is consistent with this temperature within the large error bars of the [N II] measurements.

4.5.2. Density and Temperature along P.A. 61°

We have already described (§ 4.4.3; Figs. 17a–17c) the velocity measurements from the high-resolution spectra across the nucleus at P.A. 61°. Here we measure the gas density and temperature using the 3.0 Å resolution spectrum including [N II] λλ6548, 6584, Hz, and [S II] λλ6716, 6731, and the 1.8 Å resolution spectrum including Hγ, [O III] λλ4363, Hβ, and [O III] λλ4959, 5007.

Figure 17d shows the spatial variation of the ratio \( I(\text{[NII]})_{\lambda6548 + \lambda6584}/I(\text{Hz}) \), along with 1 σ error bars (cf. Fig. 5). These are based on Gaussian fits both to the separate components and to the total line profiles. The
central gas has a high $I([\text{N}\text{ II}] \lambda 6548 + \lambda 6584)/I(\text{H}z)$ ratio, as well as a high $[\text{O}\text{ III}] \lambda 5007/\text{H}z$ ratio (Figs. 7 and 8).

Figure 17 shows the ratio $I([\text{S}\text{ II}] \lambda 6716)/I([\text{S}\text{ II}] \lambda 6731)$, which is sensitive to the electron density and temperature of the gas. The horizontal dotted lines correspond, from top to bottom, to $10^{2}, 10^{3}, 10^{4},$ and $10^{5}$ cm$^{-3}$. Ne ($10^{4}/T_e \sim 12,000$) per $T_e$ or $N_e$ for the temperatures found below. Outside this area the ratios increase, becoming consistent with the low-density limit, $N_e \leq 10^{2}$ cm$^{-3}$.

In order to measure the weak $[\text{O}\text{ III}] \lambda 4363$ line, we subtracted a template galaxy from the blue spectrum. We used a 7Å resolution spectrum of NGC 1097 kindly provided to us by T. Storchi-Bergmann. The lower resolution of the galaxy spectrum made it impossible to correctly measure broad wings on a line as weak as $\lambda 4363$, so we integrated the total flux over the same 1570 km s$^{-1}$ velocity range in all of the profiles in this spectrum and used this to calculate intensity ratios for the combined broad and narrow components.

Since $[\text{O}\text{ III}] \lambda \lambda 4363, 4959, \text{ and } 5007,$ as well as H$_{\gamma}$ and H$\beta$ are all included in a single grating setup, we made a self-contained calibration of reddening and/or flux-calibration errors. The corrected $[\text{O}\text{ III}]$ intensity ratio was calculated using $[I(H\beta)/I(H\gamma)] \times [I(H\gamma)/I(H\beta)]/0.47$. The coefficient 0.47 is the predicted $I(H\beta)/I(H\gamma)$ ratio for Case B, $T_e = 12,000$ K, $N_e = 1000$ cm$^{-3}$ (Brocklehurst 1971). The bottom panel of Figure 17 shows these results as filled circles. Where the signal-to-noise ratio is high, $T_e \sim 12,000$ K (whether or not the small reddening correction is applied).

4.5.3. FOS Results

The FOS spectra are shown in Figure 18. We attempted to take them at the brightest part of the NE arm, centered at the bend 1.4 E and 1.1 N of the nucleus. The acquisition procedure was to first center up on a star 33" away and then offset to the requested position. This had to be repeated separately for the blue and red detectors. The procedure unfortunately was not very accurate; FOS acquisition images taken after each offset show that the red spectra were in fact taken at a position 1.0 E and 0.7 N of the nucleus, while the blue spectra were taken at 0.6 E and 0.9 N of the nucleus. In both cases the peak of the narrow emission line component seen in the Fabry-Perot data ($\S$ 4.4.2) would have fallen either at the very edge of or outside of the 1" diameter aperture.

The unblended lines in these spectra have measured FWHM $\sim 600$--$800$ km s$^{-1}$, consistent with the 400--600 km s$^{-1}$ measured for the broad component in the long-slit and Fabry-Perot data for this region when convolved with the FOS instrumental width for a partly filled aperture. The measured vacuum wavelengths of the stronger unblended emission lines show a velocity offset of 250--300 km s$^{-1}$ between the spectra taken with the blue and red cameras.
This is presumably due to the 0.4 positioning difference between the two detectors, which would cause a 1.1 diode (220 km s\(^{-1}\) at 1550 Å) wavelength shift if the emission region projects, approximately, as a point source in the dispersion direction. Other sources of wavelength errors (shifts in grating or aperture position; errors in GIMP correction) are usually of order 0.1 diode and thus negligible.

The intensities of unblended lines were, therefore, measured by fitting Gaussians which had a FWHM corresponding to a 500 km s\(^{-1}\) intrinsic line width convolved with a Gaussian instrumental profile having 85% of the width expected for a completely filled aperture. The same template galaxy spectrum used above (NGC 1097) was subtracted over the rest wavelength range 3300–5300 Å before the lines were fitted. In general the wavelengths were not constrained, in order to accommodate wavelength errors, but for the H\(α\), [N II] complex, and the closely spaced C IV and Mg II doublets, wavelength spacings and, when appropriate, doublet intensities, were related. Upper limits to a number of UV multiplets seen in other AGNs were also determined by fitting multiple Gaussians with fixed separations and intensity ratios, but allowing them to slide together in wavelength (to allow for velocity uncertainties) to fit the maximum flux allowed within the noise. We did not attempt to measure the [S II] \(λ\lambda6716, 6731\) lines because of the combination of blending and the fact that \(λ6731\) has a very low signal-to-noise ratio in the unsmoothed spectrum and lies only partly in the spectrum.

The resulting intensity measurements are listed in Tables 8 and 9. The spectra taken with the red and blue detectors (above and below \(λ2200\), respectively) must be treated separately, as they were not taken at the same position.

The observed \([\text{O III}]\) intensity ratio is \(I(λ4959 + λ5007)/I(λ4363) = 150\), corresponding to \(T_e = 1.1 × 10^4\) K in the low-density limit. This is plotted as a thin horizontal line on Figure 17f, where it is seen that this temperature for the broad component may be slightly lower than the temperature derived from the sum of the two components (filled circles). Figure 17d shows that the \([\text{N II}]/\text{H}α\) ratio in the broad component, from the FOS data (thin horizontal line), is very similar to that of the sum of the components.

The emission-line spectrum measured with the red FOS detector is generally similar to those of NGC 1068 (Snijders, Netzer, & Boksenberg 1986) and the redshift \(z = 2.3\) Seyfert 2–like object 10214+4724 (Rowan-Robinson et al. 1991), with strong C II \(λ2328\) and [Ne IV] \(λ2425\). These lines and Mg II \(λ2800\) are 2–3 times weaker relative to H\(β\) than in the combined IUE and ground-based results for NGC 1068 given by Snijders et al., but that may be within the uncertainties of the effects of combining different sized apertures to form the NGC 1068 composite spectrum. The principal difference between NGC 3393 and NGC 1068 are the much broader lines in the latter, with most of the flux from the nuclear region of NGC 1068 coming from lines with FWHM ~ 2000 km s\(^{-1}\) (cf. Ciganoff et al. 1991). High-resolution spectra show these lines in NGC 1068 to have a complex structure both in spatial extent and in the velocity field (cf. Macchetto et al. 1994 or Dietrich & Wagner 1998).

Table 9 compares the UV line strengths measured here using the blue FOS to those of NGC 1068 and to an average Seyfert 2 spectrum (Ferland & Osterbrock 1986), and also to the previous IUE observations of NGC 3393 which were taken through a much larger (10" × 20") aperture. The NGC 3393 values include the small Galactic reddening correction. The other objects all have significant internal reddening, so we list both observed and dereddened values for them. Although Ly\(β\) is stronger than in NGC 1068, the Ly\(β\):C IV:C III] intensity ratio for NGC 3393 lies within the range of both the observed and dereddened values for other objects.

The upper limit on the strength of \([\text{O III}]\) \(λ1663\) shows that it is very weak relative to lines such as C IV. This is also seen in the spectrum of NGC 1068 (Marshall et al. 1993; Netzer...
The analysis in Netzer (1997) suggests that the oxygen abundance in NGC 1068 is very low, in particular that O/N and O/C are much below solar. Our observations cannot be used to put a firm limit on the O/N ratio because we do not have a reliable measurement of N in $\lambda$1750. Using the expressions in Netzer (1997) we find a conservative upper limit of O/C < 2.4, which is still consistent with solar. Better limits are necessary for a more detailed comparison with NGC 1068, and to understand whether we are seeing an ionization or an abundance effect in NGC 3393.

4.5.4. The Relativistic Gas

The steep radio spectra (§ 4.3) indicate that the radio emission is dominated by synchrotron radiation, as is generally the case for Seyfert galaxy nuclei at centimeter wavelengths (e.g., Wilson 1991). Table 10 gives the measured total and peak radio fluxes, the equipartition magnetic field, the corresponding relativistic (magnetic plus cosmic rays) pressure, and the minimum total energy. These were calculated assuming that: $h = 1$; the total energy in cosmic rays is twice that of the relativistic electrons; the radio spectrum extends from 10 MHz to 100 GHz with the spectral index given in § 4.3 for each component; the emission from the NE component comes from a cylinder of length 0.6 and radius 0.05 with its axis in the plane of the sky; the emission from the SW component comes from a sphere of radius 0.035. If, instead, the total energy in cosmic rays is taken to be 100 times that of the electrons, the pressures and total energies are larger by a factor of 9.3. The SW component is smaller and has a higher radio flux than the NE component, and so its magnetic field and pressure are higher. No estimates were made for the unresolved central component.

The pressure estimated from the radio data is of order $2-40 \times 10^{-9}$ ergs cm$^{-3}$. From the optical data ($N_e, T_e$, § 4.5) the pressure is $\sim 10^{-6}$ ergs cm$^{-3}$. The pressure of the relativistic gas is, therefore, significantly larger than the thermal pressure of the optically emitting gas.

5. DISCUSSION

5.1. Relationship with the Outer Galaxy

NGC 3393 is an early-type barred spiral, seen nearly face on. The large-scale "pseudo-ring" appears to be formed from normal spiral arms rather than shock-induced star formation from mergers (cf. most examples in Horellou et al. 1995). Buta (1995) suggests that the misalignment of the ring major axis with the expected major axis for a circular galaxy projected on the sky (§ 3.2) is an indication that the bar dominates the galactic kinematics. If the bar can dominate large-scale kinematics, then it might influence movement on smaller scales, helping to feed any "central engine" (see discussion in Capetti et al. 1996). However, Ho (1996), in a magnitude-limited sample of nearby galaxies, finds that "the presence of a bar has a negligible effect on the incidence and strength of nonstellar activity." The same result has been obtained from a near-infrared imaging survey (Mulchaey & Regan 1997).

The kinematics of the narrow component of the NLR are at least close to being consistent with the inner extension of the velocity field for a "normal" galaxy of this type; the misalignment of rotation axes between the narrow component and the outer galaxy is a modest 12° with the same sense of rotation, and the roughly solid-body rotation and velocity gradient (180 km s$^{-1}$ kpc$^{-1}$) of the narrow emission component are well within the range of the gas motions found in many "inactive" galaxies (cf. Rubin et al. 1985; Rubin 1994; Bertola et al. 1996).

5.2. Relation to Other Seyfert Galaxies

The NLR in NGC 3393 is closely associated with the radio sources. Similar associations in Seyfert galaxies have been known for many years. Both the luminosities and widths of the narrow lines are strongly correlated with the radio power (de Bruyn & Wilson 1978; Wilson & Willis 1980; Whittle 1985, 1992). The radio components have a similar spatial scale to the NLR, the pressures of the relativistic radio-emitting and thermal line-emitting gases are similar in order of magnitude, and the energy in relativistic particles and magnetic fields is comparable to the total kinetic energy of the thermal clouds. These relationships led Wilson & Willis (1980) to speculate that nuclear ejection and slowing down of radio components or jets is the process by which the high kinetic energy and ionization of the NLR...
Results from the high-resolution spectra. In all panels, broad gray lines, thick dark lines, and filled circles denote P.A. 61° results for, respectively, the broad, narrow, and total profile components, and the vertical dashed lines show the approximate position of the two radio lobes. In (a), the thin dark line is a cut through the HST [O III] image, and the total profile has been roughly normalized to the same height as the separate components. In (b) and (c), thin dark lines show Fabry-Perot results. In (d) and (f), short horizontal lines show FOS results. In (e) and (f), dotted horizontal lines show, respectively, log $N_e (10^4 T_e)$ and $10^{-4} T_e$ at the indicated values.

are maintained. Pedlar, Dyson, & Unger (1985) developed a model in which expanding radio lobes sweep up, shock, and accelerate surrounding ambient gas into shells and identified the NLR as this cooled post–bow shock gas. This picture was further developed by Taylor et al. (1989), Pedlar, Dyson, & Unger (1985) developed a model in which expanding radio lobes sweep up, shock, and accelerate surrounding ambient gas into shells and identified the NLR as this cooled post–bow shock gas. This picture was further developed by Taylor et al. (1989), Taylor, Dyson, & Axon (1992) and Ferruit et al. (1997) to include outward motion of the radio plasmon and a calculation of the line profiles expected from the postshock gas. Ground-based direct imaging (Haniff, Wilson, & Ward 1988) and long-slit spectroscopy (Whittle et al. 1988) have confirmed the close morphological and kinematic associations between the radio lobes and the line-emitting gas. Imaging observations with HST show that in some cases the gas is found along radio jets (e.g., Capetti et al. 1996; Bower et al. 1995), while in others the gas is closely associated with, and may surround, the radio lobes (e.g., Bower et al. 1994). NGC 3393 is an example of the latter.

NGC 3393 has particularly striking similarities to Mrk 573. The latter object also has arms that appear to be S-shaped and to wrap around the outer lobes of a triple radio source (Pogge & De Robertis 1995; Capetti et al. 1996), although in Mrk 573 faint connections from the ends of the S back to the nucleus can be seen in Hα so that the arms are actually “figure 8” shaped. The inner edges of the arms in both galaxies have a “corrugated” structure, suggesting they may be bow shocks driven by the expansion of high-pressure radio lobes into surrounding gas (Pedlar, Dyson, & Unger 1985). Mrk 573 has faint outer emission-line arcs, similar to the outer SW arm in NGC 3393.

Capetti et al. (1996) discuss the significance of dust lanes which cut across the nucleus of Mrk 573 and several other Seyfert 2’s, suggesting that these are outer extensions of obscuring tori. NGC 3393 again fits into the pattern, with faint dust lanes impinging into the nucleus in a P.A. roughly perpendicular to the radio axis. In this case, however, the lanes appear to connect onto spiral structure slightly farther out which may wrap around the outside of the S-shaped arms; this can be seen with close examination of the HST F606W image on an image display (this was also commented on by Pogge 1997). If the S-shaped arms are material plowed up by an expanding radio plasma the presence of dust would not be unusual (unless the gas has been shocked—§ 5.3.8), although it is unclear why the “dust lanes” are associated with just the position angles where the arms enter the nucleus rather than wrapping all the way around the bow shock; it is also possible that these lanes are actually associated with larger-scale spiral structure further out.

In addition, both galaxies have stellar bars. The bar in Mrk 573 and a number of other galaxies which are either active or have unusually blue nuclei change P.A. in their innermost regions (Capetti et al. 1996; Shaw et al. 1995). For example, in Mrk 573 there is an abrupt 90° twist at a radius of 2.5 kpc (5′). The bar in NGC 3393 does not show this behavior, but rather just becomes increasingly dominated by a circularly symmetric central bulge down to the ~1′ scale where the central dust lane starts to dominate the continuum morphology (Fig. 9). A twisted inner bar does not seem to be a necessary condition for having an active nucleus.

Mrk 573 was initially considered to be a good case of a Seyfert galaxy whose apparent NLR structure is determined by a bicone of photoionizing radiation from a nonisotropic central source. This was supported by the good fit of a detailed photoionization and kinematic model to the line intensity ratios and velocities measured from a grid of long-slit spectra (Tsvetanov & Walsh 1992). High-resolution HST images led to the reinterpretation of this NLR as a pair of bow shocks (Capetti et al 1996; Falcke, Wilson, &
Simpson 1998; Ferruit et al. 1999). A recent high spatial resolution spectroscopic study of Mrk 573 has revealed strong velocity perturbations in the vicinity of the radio components, witnessing the interaction between the radio ejecta and the ambient medium (Ferruit et al. 1999). This study also showed that the emission-line arcs are probably bow shocks driven by the radio ejecta, but that they are not photoionizing shocks, rather being photoionized by an external source of radiation. In this paper, we also use detailed velocity and spectroscopic information to investigate the similar structures in NGC 3393.

5.3. A Central Source, or Shocks, or Both?

5.3.1. Ionization Cones

Biconical patterns of highly ionized gas are frequently claimed to be signatures of photoionization from a non-isotropic central source (cf. Pogge 1989; Tadhunter & Tsveltanov 1989; Wilson et al. 1993). Figure 19a shows the $[\text{O} \text{III}]/(\text{H} \alpha + [\text{N} \text{II}])$ ratio derived by first smoothing the HST [O III] and H\alpha images with a $7 \times 7$ pixel median filter and then dividing one image by the other. Darker shades correspond to higher ionization. The high-ionization gas covers two roughly cone-shaped regions which are related to the S-shaped arms but cover a larger radial extent. The outer SW arm shows up at similarly high ionization. Calibrating the images with the Synphot software package we find that the average gray level in these areas corresponds to $I([\text{O} \text{III}])/I(\text{H} \alpha + [\text{N} \text{II}]) = 1.3$, where $I([\text{N} \text{II}])$ includes both lines in the $\lambda 6548, 6584$ doublet. This is in reasonable agreement with the ratio of 1.4 obtained from our long-slit spectra of the S-shaped arms, in which $I([\text{N} \text{II}])/I(\text{H} \alpha) = 1.3$–1.4. The lowest ionization level showing up as nonwhite on Figure 19a corresponds to a value $\log ([\text{O} \text{III}]/\text{H} \beta) \sim 0.73$ (compare to Fig. 5).

The geometry of the highly ionized gas (Fig. 19a) is consistent with ionization cones caused by anisotropic continuum emission, as in the AGN unified model. However, the area of high ionization also closely follows the regions of high line emissivity, so it is unclear whether the cones are matter-bounded or radiation-bounded. This ambiguity between density enhancements and radiation field anisotropies as a cause of the observed ionization patterns is common to many Seyfert 2's, in which the gas is aligned and cospatial with the radio source. In the illumination (ionization-bounded) picture, there should be neutral or low-ionization gas outside the apparent cones. Figure 19b shows the H\alpha + [N II] intensity in regions where $\log ([\text{O} \text{III}]/\text{H} \beta) < 0.73$, and thus shows emission from only low-ionization gas. There does appear to be low-ionization gas filling in the waist of the double-cone of highly ionized gas. Further evidence for anisotropic ionizing radiation comes from the larger-scale ionization structure shown in Figure 7. This figure reveals high-excitation gas extending $\approx 20''$ (3.6 $h^{-1}$ kpc) preferentially along a similar axis to the few arcsec scale structure, but well beyond the radio source (cf. Unger et al. 1987).

5.3.2. Energy Budget—Central Source Photoionization

HST images of NGC 3393 in the ultraviolet do not detect a central continuum source. This shows that, as is true in several other Seyferts, there are not nearly enough ionizing photons available to explain the observed Balmer recombination lines as being due to photoionization from an isotropically emitting source.
TABLE 8

LINE INTENSITIES MEASURED WITH THE FOS RED DETECTOR

<table>
<thead>
<tr>
<th>IDENTIFICATION</th>
<th>λ_{obs}^a</th>
<th>Observed</th>
<th>Corrected^c</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II λ2327.6 + λ2328.8</td>
<td>2327.0</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>[Ne iv] λ2424.7</td>
<td>2423.3</td>
<td>26</td>
<td>32</td>
</tr>
<tr>
<td>[O ii] λ2471.1</td>
<td>2469.1</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Fe II (1)</td>
<td>2626.9</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Al ii λ2660 + λ2669</td>
<td>...</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>He ii λ2734.1</td>
<td>2732.8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Mg ii λ2796.4</td>
<td>2795.9</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>Mg ii λ2803.5</td>
<td>2803.1</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>O iii λ3132.6</td>
<td>3123.1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>O iii λ3335.8</td>
<td>3133.5</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>He ii λ3204.0</td>
<td>3202.1</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>[Ne v] λ3346.9 + [Ne iii] λ3343.9</td>
<td>3344.8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>[Ne v] λ3426.8</td>
<td>3425.4</td>
<td>34</td>
<td>36</td>
</tr>
<tr>
<td>[O ii] λ3727.2 + λ3730.0</td>
<td>3726.9</td>
<td>202</td>
<td>215</td>
</tr>
<tr>
<td>H7 λ3836.5</td>
<td>3835.7</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>[Ne iii] λ3869.8</td>
<td>3868.7</td>
<td>77</td>
<td>81</td>
</tr>
<tr>
<td>He i λ3889.8 + H6 λ3890.2</td>
<td>3887.4</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>[Ne iii] λ3996.8 + He λ3970.1</td>
<td>3967.6</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>[S ii] λ4069.8, but no λ4077.5?</td>
<td>4068.9</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>H6 λ4102.9</td>
<td>4101.2</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>?</td>
<td>4225.4</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Hγ λ4341.7</td>
<td>4340.8</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>[O iii] λ4364.4</td>
<td>4364.2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>He ii λ4687.0</td>
<td>4685.1</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Hβ λ4862.7</td>
<td>4860.3</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>[O iii] λ4960.3</td>
<td>4958.6</td>
<td>334</td>
<td>332</td>
</tr>
<tr>
<td>[O iii] λ5008.2</td>
<td>5006.1</td>
<td>1032</td>
<td>1024</td>
</tr>
<tr>
<td>[N ii] λ5202.1, but no λ5200.0?</td>
<td>5201.9</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>[N ii] λ5756.4</td>
<td>...</td>
<td>&lt;8</td>
<td>&lt;8</td>
</tr>
<tr>
<td>He i λ5877.3</td>
<td>5875.0</td>
<td>≤12</td>
<td>≤11</td>
</tr>
<tr>
<td>[O i] λ6302.0</td>
<td>6300.4</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>[O i] λ6365.6</td>
<td>6363.1</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>[N ii] λ6549.9</td>
<td>6547.9</td>
<td>131</td>
<td>123</td>
</tr>
<tr>
<td>Hα λ6564.6</td>
<td>6562.6</td>
<td>319</td>
<td>300</td>
</tr>
<tr>
<td>[N ii] λ6585.2</td>
<td>6583.2</td>
<td>387</td>
<td>364</td>
</tr>
</tbody>
</table>

^a Rest-frame vacuum wavelengths are given.

^b Relative to I(Hβ) = 100. Measured I(Hβ) = 2.42 × 10^{-14} ergs cm^{-2} s^{-1}.

^c Corrected for Galactic reddening.

---

![Figure 19](image1.png)

**Fig. 19.** (a) [O iii]/(Hα + [N ii]) intensity ratio from the HST images. Darker shades correspond to a higher ratio. (b) Hα + [N ii] intensity in regions where log ([O iii]/Hβ) < 0.73 (i.e., in the low-ionization regions). Darker shades correspond to higher relative Hα + [N ii] intensity.
To see this, we follow Mulchaey et al (1994) and calculate the ratio $N_{\text{rec}}/(N_{\text{ion}} C)$. $N_{\text{rec}}$ is the number of recombinations, which we estimate from the total observed Hβ flux $F(H\beta) = 2.1 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ within a 9" × 36" rectangle centered on the nucleus and elongated in P.A. 44°. An upper limit to $N_{\text{ion}}$, the number of ionizing photons from an isotropically emitting continuum source, is calculated by extrapolating a continuum flux limit under the assumption that the energy distribution is an unreddened power law of the form $F_{\nu} \propto \nu^{-1.5}$. The tightest flux limit is set by the HST FOC image taken through the F210M filter. The 5 σ upper limit for a point source within 1.5 of the expected position of the nucleus is $F_{\nu}(2100 \text{ Å}) < 5 \times 10^{-18}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$. The covering factor is assumed to be $C \sim 0.076$, appropriate for a double-sided cone with a 45° opening angle viewed from its apex (i.e., an upper limit for a structure similar to what we observe here).

If the gas is photoionized by a central source there should be one recombination per ionizing photon. If the gas sees the same continuum as us, then we expect $N_{\text{rec}}/(N_{\text{ion}} C) = 1$. Here we find this ratio to be greater than $3 \times 10^4$. This large apparent deficit of ionizing photons could indicate that the gas sees a very much brighter source than we do, as in the standard AGN models with their “beamed” continuum sources.

5.3.3. The Shock Model

The S-shaped arms seen in the HST images each encircle a region of radio emission (assuming alignment of the central optical and radio sources—§ 4.3). This suggests that

---

**TABLE 9**
Ultraviolet Line Intensities for NGC 3393 and Other Seyfert 2 Galaxies

<table>
<thead>
<tr>
<th>Linea</th>
<th>FOS Blue ³</th>
<th>IUE 4</th>
<th>Observed ³</th>
<th>Corrected ³</th>
<th>Observed ³</th>
<th>Corrected ³</th>
<th>Observed ³</th>
<th>Corrected ³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyz $\lambda 1215.7$</td>
<td>1216.4</td>
<td>374</td>
<td>440</td>
<td>475</td>
<td>137</td>
<td>350</td>
<td>280</td>
<td>458</td>
</tr>
<tr>
<td>N $\text{v} \lambda 1238.8$</td>
<td>1239.7</td>
<td>18</td>
<td>20</td>
<td>30</td>
<td>43</td>
<td>100</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>N $\text{v} \lambda 1242.8$</td>
<td>1243.7</td>
<td>9</td>
<td>10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>O $\text{II} \lambda 1303$</td>
<td>...</td>
<td>&lt;8</td>
<td>&lt;8</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C $\text{III} \lambda 1335$</td>
<td>...</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Si $\text{iv} \lambda 1397$</td>
<td>...</td>
<td>&lt;12</td>
<td>&lt;12</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>O $\text{v} \lambda 1402$</td>
<td>...</td>
<td>18</td>
<td>18</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Si $\text{iv} + \text{O iv}$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>13</td>
<td>16</td>
<td>25</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>N $\text{v} \lambda 1486$</td>
<td>...</td>
<td>&lt;3</td>
<td>&lt;3</td>
<td>&lt;6</td>
<td>10</td>
<td>12</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C $\text{IV} \lambda 1548.2$</td>
<td>1549.6</td>
<td>64</td>
<td>64</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C $\text{IV} \lambda 1550.8$</td>
<td>1552.2</td>
<td>36</td>
<td>36</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C $\text{IV}$</td>
<td>...</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>?</td>
<td>1593.0</td>
<td>9</td>
<td>9</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>He $\text{II} \lambda 1640.7$</td>
<td>1641.5</td>
<td>38</td>
<td>37</td>
<td>58</td>
<td>36</td>
<td>56</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>O $\text{III} \lambda 1663$</td>
<td>...</td>
<td>&lt;7</td>
<td>&lt;6</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>N $\text{III} \lambda 1750$</td>
<td>...</td>
<td>&lt;9</td>
<td>&lt;8</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Si $\text{II} \lambda 1892.0$</td>
<td>...</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C $\text{III} \lambda 1908.7$</td>
<td>1908.6</td>
<td>34</td>
<td>34</td>
<td>26</td>
<td>46</td>
<td>70</td>
<td>58</td>
<td>45</td>
</tr>
</tbody>
</table>

* Rest-frame vacuum wavelengths are given.

* Relative to $I(C \text{ iv} \lambda 1549 + \lambda 1552) = 100$. Measured $I(C \text{ iv} \lambda 1549 + \lambda 1552) = 3.95 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ for NGC 3393.

* Observed values through 20" × 10" aperture corrected for Galactic reddening with $E(B-V) = 0.06$ (Diaz, Prieto, & Wamsteker 1988).

* Values corrected for Galactic and intrinsic reddening.

* Corrected for Galactic reddening.

---

**TABLE 10**
Radio Fluxes, Magnetic Field Strengths, Pressures, and Minimum Total Energy Estimates

<table>
<thead>
<tr>
<th>Component</th>
<th>Flux ³ (µJy)</th>
<th>H (G)</th>
<th>Pressure (ergs cm$^{-2}$)</th>
<th>Energy (ergs)</th>
<th>Label</th>
<th>Peak Flux ³ (µJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE 840</td>
<td>5.7 × 10$^{-4}$</td>
<td>2.7 × 10$^{-8}$</td>
<td>2.0 × 10$^{52}$</td>
<td>A</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>Core 550</td>
<td>Unresolved</td>
<td>4.3 × 10$^{-7}$</td>
<td>Unresolved</td>
<td>B</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>SW 7800</td>
<td>2.3 × 10$^{-3}$</td>
<td>1.2 × 10$^{52}$</td>
<td>Unresolved</td>
<td>C</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E</td>
<td>7100</td>
<td></td>
</tr>
</tbody>
</table>

* See Fig. 16

* Flux at 3.6 cm (8.4 GHz).
the arms are associated with a bow shock where hot outflowing gas meets cooler galactic gas, as has been proposed for the other Seyfert galaxies cited above.

Since the radio emission lies inside the optical emission the cooling time for the shocked gas must be short or it would have moved down the “cocoon” of shocked gas. It is also possible that the apparent geometry of the jets is distorted by projection effects: the line profiles in Taylor, Dyson, & Axon (1992) show that a jet which is angled toward the observer would have profiles similar to those observed and yet would not show the extreme velocity shifts present in the outflowing gas. Within the standard model, of course, the outflow could not be angled too close to the line of sight, or a Seyfert 1 would be observed.

Shock excitation alone will not produce sufficiently low temperatures in the gas, but Dopita & Sutherland (1995) have shown that, if much of the optical emission comes from gas ahead of the shock front and ionized by photons generated within this shock, consistent line ratios can be observed.

According to Dopita (1995), the shock ionization model predicts the following: optical emission from high-density material surrounding the radio lobes; a strong correlation between local velocity dispersion and local surface brightness; a correlation between local velocity dispersion and excitation; systematic velocity shifts from outflow rather than rotation; similar pressures in the NLR and radio gas (the pressure balance appears to be necessary for the turbulent mixing between the outflow and galactic gas to produce a stable “emulsion” of cool cloudlets within the hotter plasma); a correlation between radio emission, as a measure of gas pressure, and flux in forbidden line emission. However, most of these can also be explained by a situation where the gas is compressed by expanding radio lobes but photoionized by a central source (cf. Wilson, Ward, & Haniff 1988), so the presence of these correlations would not unambiguously prove that the ionization mechanism is fast shocks.

Any correlation between surface brightness and velocity dispersion should be apparent in the Fabry-Perot data. Figure 16 shows the spatial extent of the broad and narrow line components. After checking the consistency of the model with an HST image convolved to the same resolution, we believe the contours and gray-scale are positioned correctly to within one Fabry-Perot pixel (0:35). The peak of the broad line component appears to be associated with the brightest central knot, and extends SW to the brightest knot on the SW arm (the SW loop), which is the apparent location of the brightest radio source, filling in the region within the SW arm. To the NE, however, the second peak in broad line emission (Fig. 16, left panel) is not associated with the NE radio lobe, and while apparently associated with the NE arm, is not at a bright knot of optical emission. In general the broad component is much more centrally concentrated than the narrower emission.

We conclude that the widest lines do not particularly correlate with the highest surface brightness. The lines are broad right at the nucleus, but this can be understood in either the shock or the central ionizing source model as being due to virial velocities.

The ionization level also does not appear to correlate with surface brightness; this can be seen over large spatial scales by comparing Figures 10 and 19. In addition, Figure 17 shows that the [N II]/Hα ratios of the broad and narrow components are similar, although perhaps with the broad component having slightly higher [N II]/Hα on the NE side.

The densities as measured by the [S II] λ6716/λ6731 ratio, however, are significantly different in the same NE region. The temperature measured from the red FOS spectrum (§ 4.5.3) for the broad component may also be slightly lower than that for both components together measured from the P.A. 61° long-slit spectrum. This suggests that there are probably real differences between the physical conditions in the broad and narrow components at the position of the NE arm, whereas conditions are very similar in the two components in the direction of the SW arm. A lower temperature in the broad component is not consistent with the shock model since the gas should be associated with a greater degree of turbulence and, therefore, heating. If the ionization is dominated by a central source, however, the ionization state of different regions would depend on the local environment of the separate clouds.

Systematic velocity shifts are seen in the data. In § 4.4.2 we found that the narrow component appears to be generally consistent with solid body rotation. The peculiar velocities of the broad component measured from the Fabry-Perot data are unreliable (flux leakage, § 2.3), but the long-slit spectra show that, along P.A. 61°, the broad component has different velocities to those of the narrow component (Fig. 17c).

There is a much greater kinematic distinction between the two components on the SW side than on the NE side (Fig. 15). In the direction of the SW arm and all the way back to the nucleus, the velocity profile of the broad component appears to have “squarish corners” sticking out in velocity from under the narrow component profile. Robinson (1995) discusses profiles for various geometries: in this case the “corners” might be emission from an expanding shell (the “sides” of the arms). On the NE side the broad component merges smoothly into the wings of the narrow component, so that the only evidence for two distinct components is provided by the difference in density. The difference in behavior on the two sides of the nucleus can be seen in the velocity cut shown in Figure 17c, where the broad and narrow component velocities are fairly similar on the NE side but show a 100 km s⁻¹ difference to the SW.

5.3.4. Energy Budget—Shock Ionization

We have already noted that the HST observations imply that the UV flux from a central source is over 3 × 10⁴ too small to account for the Hβ flux (§ 5.3.2). Can the same argument be applied to the sources of UV flux expected from shocked gas?

In the shock model, UV and soft X-rays are generated within the shock front and ionize the nearby galactic gas (Bicknell 1994). We would therefore expect to see UV continuum emission closely following the pattern of the S-shaped arms, but possibly slightly inside them. To test for this, we used our WFPC Hα image to create a mask set to one in the brighter regions of the S-shaped arms lying more than 0:6 from the nucleus, and to zero everywhere else. This mask was resampled to the scale and orientation of the FOC 2100 Å continuum image, except that it was reduced in size by a factor 0.95 to shift the pattern in toward the nucleus by 1/3 the arm width. The FOC image was multiplied by this mask to determine the total counts within the S-shaped pattern. This was done with the mask center shifted to 100 different points within the FOC image. The mean of
these measurements represents the background, and their standard deviation the 1 σ measuring uncertainty.

Inspection of the FOC image shows a possible S-shaped continuum feature near to the expected nominal position, shifted 0:21 N and 0:43 W (well within the HST pointing uncertainty). When measured using the mask shifted to this position, this turns out to be a 1.2 σ feature. We will instead use the 5 σ upper limit, which is \( F_{\lambda}(2100 \, \text{Å}) < 1.2 \times 10^{-15} \text{ergs cm}^{-2} \text{s}^{-1} \cdot \text{Å}^{-1} \). This is 240 times higher than the upper limit on a central point source.

The production of ionizing photons within the turbulent region will be dominated by fast shocks and these are expected to produce a pseudo-continuum (including EUV emission lines) which is much harder than the canonical \( F_{\nu} \propto \nu^{-1.5} \) AGN power law in the UV and soft X-ray range. Morse, Raymond, & Wilson (1996) find that, for the same \( F_{\lambda}(1300 \, \text{Å}) \) flux limit, there should be \( \sim 100 \) times more ionizing photons in the shock model than in the power law. A similar factor will apply to the 2100 Å continuum point used here.

Finally, the covering factor of the photoionized gas, seen from within the shock region, should be \( C \sim 0.5 \) (this is the upper limit, assuming that the “swept up” gas has been sufficiently compressed to form a continuous layer), which is 7 times larger than the factor used for the model of a double bicone illuminated from a central source.

In § 5.3.2 we found that for a central point source \( N_{\text{rec}}/(N_{\text{ion}} \, C) > 3 \times 10^4 \). Correcting this limit downward by factors of 240, 100, and 7, we find that for the shock ionization mechanism \( N_{\text{rec}}/(N_{\text{ion}} \, C) > 0.2 \), consistent with an expected value of 1. Therefore, fast shocks are a viable source of photoionizing photons, especially given the possible 1.2 σ detection of an S-shaped continuum source (which, if used, gives \( N_{\text{rec}}/(N_{\text{ion}} \, C) \sim 1 \)). This possible source should either be detected or ruled out by an HST image going 10 times deeper. The IUE spectra through the 10″ × 20″ aperture (Diaz et al. 1988) do show a flat continuum with \( F_{\lambda}(2100 \, \text{Å}) \sim 2 \times 10^{-15} \text{ergs cm}^{-2} \text{s}^{-1} \cdot \text{Å}^{-1} \), twice our 5 σ upper limit and 6 times our possible detection. This could be taken either to confirm our possible detection within the large uncertainties of both observations, or to indicate that most of the UV flux comes from a more extended source than we can detect. If present, a diffuse UV source could be due to light scattered from dust or electrons in the arms rather than to radiation from shocked gas in the arms; it is the absence of such diffuse emission (if proven) that would lead to the strongest conclusion about the ionization mechanism.

5.3.5. Energy Budget—Outflow

The maximum energy flux (erg s\(^{-1}\)) available from two outflows of ionized gas, each with a radius of 50 h\(^{-1}\) pc, density of \( N_{e} \) cm\(^{-3}\), temperature \( T \) K, and a velocity of \( v \) km s\(^{-1}\) is

\[
6.7 \times 10^{43} \frac{h^{-2} \, N_{e}}{10^3} \left( \frac{v}{800} \right)^3 + 1.3 \times 10^{-4} \frac{T}{10^4} \frac{v}{800}.
\]

The outflow velocity is estimated to be approximately equal to the 800 km s\(^{-1}\) width of the broadest lines because, as noted by Bicknell (1994), “the Kelvin-Helmholtz instability is capable of producing velocities in the dense material equal to a substantial fraction of the free stream velocity.”

Integrating the H\(\beta\) flux (§ 5.3.2), assuming that there are eight recombinations per H\(\beta\) photon, and scaling this by 13.6 eV, gives a lower bound on the energy required to keep the gas ionized of \( 2 \times 10^{42} h^{-2} \) ergs s\(^{-1}\). This is a strong lower limit since it assumes that every ionizing photon has the lowest possible energy, and that all ionizing photons are absorbed. A power-law spectrum of the form \( F_{\nu} \propto \nu^{-1.5} \), for example, is 3 times less efficient, and a typical efficiency/covering factor might be 0.5. As an estimate of the energy required, therefore, we will use \( 10^{43} h^{-2} \) ergs s\(^{-1}\).

Comparison with the above equation shows that the energy budget will be satisfied for any density greater than 150 h\(^{-2}\) cm\(^{-3}\). Furthermore, lower density, higher velocity outflowing gas would not radiate sufficient optical line emission to be detected by our observations but could contribute to the kinetic energy available to power the observed line emission. Thus, our data are energetically consistent with the NLR being powered by the outflow.

5.3.6. Spatial Structure

For an outflow speed of \( v \) km s\(^{-1}\) the distance of the arms from the nucleus gives a lower limit on the age of each structure of about \( 3 \times 10^3 \) (1000/v) h\(^{-1}\) yr. The extended SW emission, which is similar in structure to the arms, could be an older feature with an age of \( 8 \times 10^5 \) (1000/v) h\(^{-1}\) yr (assuming that the arms lie roughly in the plane of the sky). Similar series of roughly concentric arcs are seen in other Seyfert 2 galaxies (NGC 5252, Tadhunter & Tsvetanov 1989; Mrk 573, Capetti et al. 1996; Ferruit et al. 1999).

The more distant SW arc suggests that the outflow varies in some way—possibly occurring as discrete “plasmons” (Taylor et al. 1989).

Whether the emission-line arms are bow shocks or not, their exact shape is difficult to explain. The higher density in this region (Fig. 17) and the apparent association with the radio emission has already been discussed, but bow shocks do not explain why the emission is an S rather than an 8. Galactic rotation, which might sweep gas onto the radio lobes, is in the opposite sense (assuming trailing arms) to that expected. It is also interesting that simulations of bars can show structures very similar to those seen here, although at larger scales in present models (Athanassoula 1992).

5.3.7. Diagnostic Line Intensity Ratios

In many Seyfert 2 galaxies and extended narrow-line regions the [O III] ratio indicates \( T_{e} \geq 14,000 \) K. Temperatures that high cannot be produced by optically thick gas of solar abundance photoionized by a power law with the usually accepted slope, but a mixture of optically thin and optically thick clouds can reproduce these temperatures along with the wide range of (He II \( 4686)/H\beta\) intensity ratios and the strong, high-ionization lines often seen in these objects (Binette, Wilson, & Storchi-Bergmann 1996).

The \( T_{e}\) values measured for NGC 3393 are somewhat lower than usual and are consistent with a single optically thick component. Comparing all of our observations of the central region to the diagnostic diagrams presented by Binette et al. shows that all intensity ratios, including the He II/H\beta\) ratio and the strength of the [Ne v] \( 3346\) lines are as consistent with optically thick gas as with a mixture of optically thick and thin gas. For example, over the well-measured region in the P.A. 61° long-slit spectra, \( I(\text{He II} 4686)/I(H\beta) = 0.31 \) the same as the ratio predicted by Binette et al. in their optically thick model with solar abun-
dances. The FOS spectrum indicates a somewhat lower value of 0.25 for this ratio which may still be explainable with just optically thick clouds. However, it is not possible to fit all of the observed intensity ratios with an optically thick model having a single ionization parameter.

Line ratios for the shock model have been calculated by Dopita & Sutherland (1995). In almost all of their diagnostic diagrams the NGC 3393 intensity ratios fall very close to the curves predicted for 500 km s$^{-1}$ shocks plus photoionized precursors, and far away from the “shock only” curves. The exception is on their log ($\lambda 5007$/H$\beta$) versus log ($\lambda 6300$/H$\alpha$) diagram, where in common with most of the Seyfert galaxies the NGC 3393 values do not fall near any of the predicted curves.

The major failure in the models photoionized by a central source is their inability to reproduce the very high observed intensity ratio $I([\text{N}\ II]/\lambda 6584)/I([\text{O}\ II]/\lambda 3727)$ ~ 2 (cf. Schmitt et al. 1994). Models combining AGN photoionization with some shock heating can fit this ratio much better (Viegas & de Gouveia Dal Pino 1992). This is the only piece of evidence from the NGC 3393 intensity ratios which suggests a significant energy input from shocks rather than a central source. However, an alternative explanation is that the N/O abundance ratio is enhanced as has been suggested for a number of other Seyfert galaxies (e.g., Storchi-Bergmann et al. 1996 and references therein).

Observations which would help distinguish between shocks and photoionization from a central source, but which are missing from this analysis, are the normalization of the lines seen in the blue FOS spectrum (Ly$\alpha$, C IV, C III$^+$) to the optical lines, and any measurements of the lines below Ly$\alpha$. Including the UV lines would offer a further test of whether a mix of optically thin and thick gas is needed for photoionization, and perhaps of whether there is the wide range of temperatures predicted by shock heating (Allen et al. 1998). Kriss et al. (1992) have argued that the latter occurs in NGC 1068, based on line ratios such as C III$^+$ $I(\lambda 977)/I(\lambda 1909)$ and N III$^+$ $I(\lambda 1750)/I(\lambda 991)$. However, Ferguson, Ferland, & Pradhan (1995) showed that processes found in photoionized gas also can cause the $\lambda 977$ and $\lambda 991$ lines to be strong. In addition, it is unclear whether both lines in the pairs from the same ion are actually emitted from the same elements of gas.

5.3.8. Grain Destruction in Shocks

If interstellar grains are destroyed by shocks and can only be regenerated on the long timescales associated with formation in stellar envelopes, then the intensity of the emission lines of refractory elements will be a sensitive tracer of postshocked gas (Ferland 1993; Kingdon, Ferland, & Feibelman 1995). Gas that has gone through a shock is predicted to have very strong lines of [Ca II], Al II, and Mg II that would be suppressed if these elements were still locked up in grains.

The intensity ratios $I([\text{Ca}\ II]/\lambda 2328 + 2329)/I([\text{S}\ II]/\lambda 6716 + 6731)$, $I(\text{Al} \ II)/I(\text{C}\ II/\lambda 2232 + 2239)$, and $I(\text{Mg} \ II/\lambda 2796 + 2803)/I(\text{C}\ II/\lambda 2232 + 2239)$ are insensitive to many nebular parameters and therefore are good abundance indicators (Kingdon et al. 1995). We have used the photoionization code Cloudy (Ferland 1997) to compute the predicted ratios of these lines for both solar and depleted abundances, over a wide range in the ionization parameter $U$ with $N_e = 10^8$ cm$^{-3}$. The ionizing continuum was the Mathews & Ferland (1987) AGN continuum with the submillimeter break at 10 $\mu$m.

The solar and depleted abundances are given by Baldwin et al. (1991), and the grains are the large-R molecular cloud grains described there. The specific abundances used in the H II region mix are H, 1.0; He, 9.5 $\times 10^{-2}$; C, 3.0 $\times 10^{-4}$; N, 7.0 $\times 10^{-5}$; O, 4.0 $\times 10^{-4}$; Ne, 6.0 $\times 10^{-5}$; Na, 3.0 $\times 10^{-7}$; Mg, 3.0 $\times 10^{-6}$; Al, 2.0 $\times 10^{-7}$; Si, 4.0 $\times 10^{-6}$; S, 1.0 $\times 10^{-5}$; Cl, 1.0 $\times 10^{-7}$; Ar, 3.0 $\times 10^{-6}$; Ca, 2.0 $\times 10^{-8}$; Fe, 3.0 $\times 10^{-8}$; Ni, 1.0 $\times 10^{-7}$.

From the spectrum at P.A. 61°, the observed limit in the NE arm is $I([\text{Ca}\ II]/I([\text{S}\ II])/0.007$. From the FOS spectrum (Table 8), in the region between the NE arm and the nucleus $I(\text{Al} \ II)/I(\text{C} \ II) < 0.04$ and $I(\text{Mg} \ II)/I(\text{C} \ II) = 1.7$. These values are also marked on Figure 20.

It is seen that over most of the range in $U$, [Ca II] is a factor 10 weaker than expected for solar abundances and indicates abundances close to the depleted Orion Nebula values. The Mg II strength and the upper limit on Al II also indicate significant depletion onto dust grains. The difference between the amounts of depletion suggested by the Mg II/C II and [Ca II]/S II results is within the range of uncertainties in the relative abundances. This is especially true given that these abundances vary within galaxies, and the [Ca II] upper limit is measured from our long-slit spectra and is for the broad and narrow components together, while the Mg II and the Al II upper limit are measured from the FOS spectrum which includes just the broader line component (§4.5.3).

The refractory line strengths thus suggest that this gas has not recently passed through a shock.

---

***Figure 20.*** Predicted and observed intensity ratios involving the refractory elements, as a function of the ionization parameter $U$ for an AGN ionizing continuum and $N_e = 10^8$ cm$^{-3}$. Solid curved lines are predicted values for solar abundances and no depletion on grains, the dashed lines are for depletion as described in the text. Observed values or upper limits are shown as short horizontal lines.
6. CONCLUSIONS

In common with many other Seyfert 2 galaxies, NGC 3393 is found to have a complex NLR which is intimately associated with an extended radio source (§ 4.3). On the scale of a few arcseconds, the structure of the line emission appears to be dominated by effects of the radio lobes. At low resolution this gives an apparently "biconical" structure to the NLR which is not necessarily related to obscuration of a central ionizing source (§ 5.3.1). In common with results from several other Seyfert 2's (§ 5.2), this has two implications for the simple unified model. First, radio lobes may strongly affect the structure of the NLR. Second, emission from the shocked boundary of the radio lobes may be an important source of ionizing radiation.

Several tests of the photoionizing shock model are inconsistent with our observations: we do not see any intercorrelations between local velocity dispersion, surface brightness, and excitation (§ 5.3.3). Nor does a significant fraction of the optically emitting gas appear to have been shocked (§ 5.3.8). A central source is, therefore, likely to be the main source of ionizing radiation. However, there is sufficient kinetic energy associated with the outflow to power the line emission (§ 5.3.5), and if the 1.2 $\sigma$ detection of an S-shaped UV continuum source turns out to be correct it will have approximately the right intensity to be the shock-generated ionizing radiation (§ 5.3.4) (although it could also be reflected nuclear light).

Our analysis indicates that outflow is important in forming the structure that we see in the optical images and, especially, in generating the radio emission (§ 5.3). Almost all of the optical line ratios can be explained (§ 5.3.7) by models assuming that either radiation bounded clouds alone, or a mixture of matter and radiation bounded clouds, are photoionized by a central source that is obscured from our line of sight (§ 5.3.2). The exception is the I($[\text{N}\;\text{II}]/\lambda 6584$)/I($[\text{O}\;\text{II}]/\lambda 3727$) ratio, which may indicate that shock ionization, while not dominant, plays a role, or that the N/O abundance ratio is enhanced.

Since the optically emitting gas with narrower line widths appears to be rotating as a solid body, it seems likely that the central galactic gas is in a disk structure rotating nearly in the plane of the parent galaxy (§ 4.4.2). The broader emission lines, being more centrally concentrated, are more likely to be associated with the interaction between the gas and the radio lobes. This is supported by the relationship between the radio and optical data (§ 4.3).

In general, our detailed study of NGC 3393 does not support the hypothesis that autoionizing shocks are the primary source of ionization in this sort of galaxy. Rather, the radio lobes appear to have created denser regions of gas on their leading edges which form the S-shaped arms, but the ionization is most likely due to photoionization from an obscured central source (§ 5.3.1, Fig. 19).

John Biretta and the WFPC group at STScI kindly supplied early flat-field calibration files. A. J. C. would like to thank the CTIO for their kind hospitality while he was working on this project, while J. A. B. wishes to thank the Institute of Astronomy, Cambridge, for similar hospitality. A. J. C., J. A. B., and G. J. F. gratefully acknowledge support by STScI grants GO-2306.01-87A and GO-06093.01-94A during parts of this work. A. S. W. was supported in part by NASA grant NAG81027 and STScI grants GO-6006 and GO-6419. This research was supported in part by a grant from the Israel Science Foundation and the USA–Israel Binational Science Foundation. We acknowledge the use of computer resources provided by the Starlink Project, which is funded by PPARC.

REFERENCES
