IS A MINOR MERGER DRIVING THE NUCLEAR ACTIVITY IN THE SEYFERT 2 GALAXY NGC 2110?

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ABSTRACT

We report on a detailed morphological and kinematic study of the isolated nonbarred nearby Seyfert 2 galaxy NGC 2110. We combine integral field optical spectroscopy with long-slit and WFPC2 imaging available in the *Hubble Space Telescope* archive to investigate the fueling mechanism in this galaxy. Previous work (Wilson & Baldwin) concluded that the kinematic center of the galaxy is displaced ~ 220 pc from the apparent mass center of the galaxy, and the ionized gas follows a remarkably normal rotation curve. Our analysis, which is based on the stellar kinematics, two-dimensional ionized gas velocity field and dispersion velocity, and high spatial resolution morphology at V , I , and $H\alpha$, reveals the following: (1) The kinematic center of NGC 2110 is at the nucleus of the galaxy. (2) The ionized gas is not in pure rotational motion. (3) The morphology of the two-dimensional distribution of the emission-line widths suggests the presence of a minor axis galactic outflow. (4) The nucleus is blueshifted with respect to the stellar systemic velocity, suggesting the narrow-line region gas is outflowing owing to the interaction with the radio jet. (5) The ionized gas is redshifted ~ 100 km s^{−1} over the corresponding rotational motion south of the nucleus and 240 km s^{−1} with respect to the nuclear stellar systemic velocity. This velocity is coincident with the H I redshifted absorption velocity detected by Gallimore et al. We discuss the possibility that the kinematics of the south ionized gas could be perturbed by a collision with a small satellite that impacted on NGC 2110 close to the center with a highly inclined orbit. Additional supports for this interpretation are the radial dust lanes and tidal debris detected in the V unsharp-masked image. We suggest that a minor merger may have driven the nuclear activity in NGC 2110.

Subject headings: galaxies: active — galaxies: individual (NGC 2110) —
 galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: Seyfert

On-line material: color figures

1. INTRODUCTION

The two most important questions concerning active galactic nuclei (AGNs) are the fundamental nature of their energy source and the mechanism by which the nuclear activity is fueled. Even though it is widely accepted that the energy source originates in the accretion of mass onto a central supermassive black hole, starbursts could also play an important role in the same galaxies (e.g., González Delgado 2002; Veilleux 2001 and references therein). In fact, many examples have been reported in which the two phenomena coexist. At the high-luminosity regime, ultraluminous infrared galaxies are the best examples (Lutz & Tacconi 1999). Powerful starbursts are also found in the central ~ 100 pc of less luminous AGNs, such as Seyfert 2 galaxies (Heckman et al. 1997; González Delgado et al. 1998), and even at smaller spatial scales ($\sim$ few parsecs), as it is the case of the low-luminosity AGN NGC 4303 (Colina et al. 2002).

The origin of the gas that fuels the central engine and the mechanism that brings the gas to the very central region are still controversial. Observations of high-luminosity AGNs

indicate that quasars and ultraluminous infrared galaxies have been gas-rich mergers (Sanders et al. 1988; Canalizo & Stockton 2001). However, in low-luminosity AGNs, the fueling mechanism remains unclear. Early investigations of Seyfert galaxies have also suggested that galaxy interaction could provide the gas fueling onto the supermassive black hole (e.g., Noguchi 1988; Mihos & Hernquist 1996). Early research suggested that there is an excess of companions in Seyfert galaxies (Dahari 1984). However, this result has not been confirmed more recently (De Robertis, Yee, & Hayhoe 1998; Rafanelli, Violato, & Baruffolo 1995). Thus, the galaxy interaction hypothesis can be ruled out as the main fueling mechanism in Seyfert galaxies.

The nonaxisymmetric gravitational potential originated by a large-scale bar in the host galaxy has also been suggested as an efficient way to drive the gas to the central region (Shlosman, Begelman, & Frank 1990; Athanassoula 1992). However, it can be ruled out as a general mechanism because an excess of bars in Seyfert galaxies has not been confirmed observationally (Adams 1977; Moles, Márquez, & Pérez 1995; Hunt et al. 1997; Maiolino, Risaliti, & Salvati 1999). Studies based on near-infrared imaging, known to trace the stellar bars better than the optical observations,

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also arrive at contradictory results. Based on *Hubble Space Telescope* (*HST*) NICMOS observations, Mulchaey & Regan (1997), Regan & Mulchaey (1999), and Martini & Pogge (1999) find no evidence for an excess of stellar bars in Seyfert galaxies. On the other hand, Knapen, Shlosman, & Peletier (2000) found an excess in the sample of CfA Seyfert galaxies with respect to a control sample. However, this excess of bars in CfA Seyfert galaxies disappears when galaxies that are in interaction are excluded from the statistics (Márquez et al. 2000).

Minor merger between a disk galaxy and a nucleated less massive galaxy is also proposed as an alternative fueling mechanism (García-Lorenzo et al. 1997; de Robertis et al. 1998; Taniguchi 1999). In this context, it is interesting to note that some kinematic peculiarities found in NGC 1068 have been interpreted by García-Lorenzo et al. (1997; García-Lorenzo, Mediavilla, & Arribas 1999) as the result of a minor merger event. Since most galaxies have satellites (Zaritsky et al. 1997), it is likely that minor mergers drive the fueling mechanism for most of the isolated Seyfert galaxies. However, there is not yet observational proof of this scenario.

NGC 2110 is a nearby (~ 31 Mpc), early-type S0, isolated galaxy showing a Seyfert 2 nucleus (McClintok et al. 1979; Shuder 1980). This galaxy has been extensively studied at radio, NIR, optical, UV, and X-ray wavelengths. These studies have revealed a number of interesting properties in this object, making it a good target to investigate the minor-merger hypothesis as the mechanism that drives the gas to the center and feeds the AGN in NGC 2110. Its main properties can be summarized as follows:

1. It is classified as a narrow-line X-ray galaxy (Bradt et al. 1978) because of the strong X-ray emission, having a hard X-ray luminosity (2–10 KeV) comparable to those of Seyfert 1 galaxies (Weaver et al. 1995). Soft X-ray emission is also detected at $4''$ north of the nucleus (Weaver et al. 1995).

2. VLA radio continuum maps reveal a symmetrical jet-like radio emission extended $4''$ along the north-south direction (Ulvestad & Wilson 1983; Nagar et al. 1999). More recent VLBA observations at 3.6 cm also show a compact (≤ 1 pc) radio core aligned with the 400 pc scale radio jet (Mundell et al. 2000).

3. Ground-based narrowband ([O III] and $H\alpha$ + [N II]) images reveal extended emission up to $10''$ showing an S-shape morphology in the north-south direction (Wilson, Baldwin, & Ulvestad 1985; Pogge 1989). *HST* pre-COSTAR [O III] and $H\alpha$ + [N II] images confirm the alignment of the optical and radio jet, but only a loose anticorrelation between the brightest optical and radio knots was found (Mulchaey et al. 1994). Ferruit et al. (1999) have obtained *HST*+FOC UV and optical spectra of the jet to investigate the mechanism that ionizes the extended gas. They suggest that the ionized high-excitation gas is produced by photoionization by fast shock waves probably generated by the propagation of the radio ejecta into the interstellar medium of the host galaxy. Shocks, driven by the radio jet, could also be responsible for the strong [Fe II] $\lambda 1.2567 \mu\text{m}$ nebular emission detected in its nuclear and circumnuclear region (Storchi-Bergmann et al. 1999; Knop et al. 2001).

4. From the morphological point of view, the optical continuum (Malkan, Varoujan, & Raymond 1998) and

NICMOS/WFPC color maps (Quillen et al. 1999) show clear asymmetries in the central region. Dust lanes at $1''$ and $4''$ to the west of the nucleus are detected.

5. The nuclear stellar population was studied by González Delgado, Heckman, & Leitherer (2001) to look for signatures of starbursts. Its optical continuum (stellar features and spectral energy distribution) is well explained by an old stellar population with a small contribution from a power law. Thus, no obvious signs of a young (age ≤ 1 Gyr) stellar population were found.

6. The kinematics of the circumnuclear ionized gas region was studied by Wilson & Baldwin (1985) and Wilson et al. (1985). They reported a rotation pattern remarkably similar to that expected for spiral galaxies. They also found that the rotation center was not coincident with the optical (and radio) nucleus but was located $1''.7$ (220 pc) to the south of the nucleus. They also reported the presence of asymmetric profiles in the [O III] nebular lines, south and east of the nucleus.

7. H I absorption has been detected in NGC 2110 by Galimore et al. (1999), located south of the maximum of the radio continuum source. This absorption has a velocity of 2626 km s^{-1} and is redshifted by about 290 km s^{-1} with respect to the systemic velocity, 2335 km s^{-1} , calculated by Strauss et al. (1992) using the nuclear optical emission lines.

Here we present new integral field spectroscopic (IFS) data at optical wavelengths of the circumnuclear region of NGC 2110. This technique is ideal for studying an asymmetric and complex object like NGC 2110 since it provides two-dimensional spectral information of relevant spectral features (i.e., velocity fields, velocity dispersion maps, line intensity maps, continuum maps, etc.) simultaneously and, therefore, without the uncertainties associated with centering, reference systems, and so on. In addition to these IFS data, we also present new long-slit spectroscopy to study the stellar kinematics. These data, together with some WFPC2 images retrieved from the *HST* archive, allow us to investigate the kinematic peculiarities found in NGC 2110 and their possible connection with the fueling mechanism of the AGN in NGC 2110. The paper is organized as follows: In § 2 we present the observations and data reduction. Section 3 presents the analysis of the stellar and ionized gas distribution, and § 4 presents the gas and stellar kinematics. We discuss our results and their implications in § 5. The conclusions and summary are in § 6.

2. OBSERVATIONS AND DATA REDUCTION

Two types of observations have been carried out: (1) integral field spectroscopy and (2) long-slit spectroscopy. In addition, *HST* WFPC2 images have been retrieved from the ST-ECF archive.

2.1. Integral Field Spectroscopy

NGC 2110 was observed with the INTEGRAL system (Arribas et al. 1998) and the Wide Field Fiber Optic Spectrograph (Bingham et al. 1994) attached to the 4.2 m William Herschel Telescope at the Roque de los Muchachos Observatory during 1999 February 10. We used the SB2 bundle of fibers, consisting of 219 fibers with a core diameter of $0''.9$ each. The 189 data fibers are arranged forming a rectangle with a $16''.5 \times 12''.3$ field of view. A ring of 30 fibers, at $45''$ from the center, is intended for collecting the back-

ground light. We observed with the R600B grating, covering the 3700–7000 Å spectral range with a linear dispersion of 3 Å pixel⁻¹. The mean effective spectral resolution is 5.3 Å. The total integration time was 7200 s, split into four 1800 s exposures. The air mass of the object during the observations was between 1.25 and 1.45, and the seeing $\sim 1''.0$ – $1''.2$.

The reduction of the spectra was performed with the IRAF² data processing software. We followed the standard procedures applied to spectra obtained with two-dimensional fiber spectrographs (Arribas et al. 1997). They consist of (1) bias subtraction, (2) cosmic-ray rejection, (3) definition and extraction of the 219 apertures, (4) arc line identification and dispersion correction, (5) flat-field and throughput correction, (6) sky subtraction, and (7) atmospheric extinction correction and flux calibration. The typical wavelength calibration error 0.2–0.3 Å, gives velocity uncertainties of 10–15 km s⁻¹.

To do the flux calibration we have also observed with the bundle SB2 the spectroscopic standard Feige 34. Two 180 s exposures were taken; one of them was taken through a color filter that blocks the second-order blue light from wavelengths below 4950 Å. The sensitivity function was built using the stellar spectrum of one of the fibers, then scaling it by a factor that represents the fraction of the flux detected by this fiber with respect to the total flux.

2.2. Analysis of the Integral Field Data

Two-dimensional maps of some spectral features, such as continuum, absorption-line equivalent-width, line emission fluxes, and radial and dispersion velocity were obtained from the fibers' individual spectra with a program that uses a Renka+Cline two-dimensional interpolation method. This routine (NAG-E01SAF) transforms a file with the actual position of the fibers in the focal plane of the telescope and the spectral feature into a regularly spaced image, and it guarantees that the constructed surface is continuous and has continuous first derivatives. The interpolant is then evaluated regularly each 0''.0846 on a grid of 201 × 201 pixels to create the maps. Note that the continuity conditions imposed to the interpolant allows one to evaluate it with a fine sampling. Although this procedure does not modify the effective spatial resolution, it improves the general appearance of the maps.

Prior to interpolation, the kinematical and line intensity information for each fiber was obtained measuring the main nebular lines, such as H β , [O III] $\lambda 5007$, [O I] $\lambda 6300$, H α , [N II] $\lambda 6584$, and [S II] $\lambda \lambda 6717, 6731$. The measurements were done by fitting Gaussians to the nebular lines using the program LONGSLIT (Wilkins & Axon 1991). These fits determine the central wavelength, the emission-line width, the flux, and the continuum. Alternatively, the continuum and emission-line images were also obtained, integrating the fluxes between appropriate wavelength ranges. These images reveal the same continuum and nebular emission structures as those obtained by fitting Gaussians to the nebular lines. The image obtained as the difference between the map obtained through the Gaussian fitting procedure and that obtained integrating the fluxes does not show any sig-

nificant residual emission structure. Thus, this result indicates that the Gaussian fitting method works well to provide the continuum and emission-line structures of NGC 2110.

2.3. Long-Slit Spectroscopy

NGC 2110 was observed using the Richey-Chretien spectrograph attached to 4 m Mayall Telescope at the KPNO during 1996 February 15 and 16. The detector was a T2KB CCD chip with a spatial sampling of 0''.7 pixel⁻¹. The slit width was set to 1''.5, and it was oriented near the parallactic angle, P.A. = 6°. We used the gratings BL420 and KPC-007 to cover the spectral ranges 6600–9100 Å and 3400–5500 Å, respectively. The linear dispersion is 1.52 Å pixel⁻¹ for the red and 1.39 Å pixel⁻¹ for blue spectral range. The effective spectral resolution is ~ 3 Å. One exposure of 1800 s was taken at the red, and two exposures of 900 s each were taken at the blue wavelengths. The seeing was about 1''.5.

Data reduction was performed using the FIGARO³ data processing software. We followed the standard procedures applied to long-slit spectra: (1) bias and flat-field correction, (2) two-dimensional wavelength calibration using ARC2D (Wilkins & Axon 1991), and (3) atmospheric extinction correction and flux calibration. Several spectroscopic standards were observed with a 10'' wide slit during the night. In addition, several velocity template K giant stars were observed for the kinematic analysis.

2.4. HST Archival Data

We obtained three sets of WFPC2 images of NGC 2110 from the ST-ECF *HST* archive. The images were taken through three different filters: F606W, F919W, and FR680P15. The filter F606W ($\lambda = 6010.6$ Å, $\delta\lambda = 1497$ Å) (PI M. A. Malkan) includes emission from the strong lines [O III] $\lambda 5007$ and H α . The integration time was 500 s. The filter F919W ($\lambda = 8006$ Å, $\delta\lambda = 1304$ Å) (PI C. G. Mundell) transmits mainly the red continuum of the object, and it is free of contamination from strong emission lines; we refer to it as the *I* image. The integration consisted of 2 × 120 s exposures. FR680P15 (PI C. G. Mundell) is a linear ramp filter designed to observe the emission-line H α . The band is centered at 6610 Å, and it has a width of 41 Å; this filter also includes the emission-line [N II] $\lambda 6548$. The unvignetted field of view through this filter is about 9''. The total integration time of 1200 s was split into four exposures. We refer to it as H α . The three sets of observations place the nucleus of NGC 2110 in the WFPC2 (PC) image. The central part of NGC 2110 (corresponding to most of the emission detected in the galaxy) is thus sampled at 0''.046 pixel⁻¹.

We use the standard pipeline reduction procedures. The individual frames of the *I* and H α images were combined with *crreject* command to eliminate the cosmic rays. To produce a continuum-free H α image, the *I* image was scaled down by a factor of 3 and subtracted from the H α plus underlying continuum. The scaling of the *I* image was performed by visual inspection through photometric cuts along the major and minor axes. This method was preferred to the direct scaling of the filter widths, because as seen in the spectra (see Fig. 2) the continuum is quite red; thus there is a strong color component in the scaling from *I* to the H α wavelength band that is position dependent.

² IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

³ Software from the Starlink Project funded by the UK PPARC.

3. STELLAR AND IONIZED GAS DISTRIBUTION

Figure 1 shows the individual calibrated spectra corresponding to the 189 fibers in the spectral ranges that include $H\beta$ and $[O\ III]\ \lambda\lambda 4959, 5007$ (Fig. 1a) and $H\alpha$ and $[N\ II]\ \lambda\lambda 6548, 6584$ (Fig. 1b). Figure 2 shows the nuclear spectrum from the fiber 110, which corresponds to the maximum of the continuum and presumably the AGN, and two circum-

FIG. 1a

FIG. 1b

FIG. 1.—Final calibrated circumnuclear ($16''.5 \times 12''.3$) spectra of NGC 2110 in the spectral ranges (a) $\lambda\lambda 4870\text{--}5080$, including $H\beta$ and $[O\ III]\ \lambda\lambda 4959, 5007$, and (b) $\lambda\lambda 6650\text{--}6685$, including $H\alpha$ and $[N\ II]\ \lambda\lambda 6548, 6584$. The numbers in the plot indicate the number of the fiber at the entrance of the spectrograph. North is up, and east is to the left. This is the orientation in all the images. The 180 spectra are autoscaled.

FIG. 2.—Nuclear and two circumnuclear spectra of NGC 2110, corresponding to the fibers 110 (nucleus), 100 ($\sim 2''$ south of the nucleus), and 123 ($\sim 3''$ north of the nucleus). The circumnuclear spectra are shifted by 2 and 2.3×10^{-15} ergs $s^{-1} cm^{-2} \text{\AA}^{-1}$. Note the strong gradient along the excitation in the north-south direction.

nuclear spectra corresponding to fiber 123 ($\sim 3''$ north from the nucleus) and fiber 110 ($\sim 2''$ south from the nucleus). These two spectra have been chosen to show the north-south asymmetry in the excitation, measured as the $[O\ III]/H\beta$ ratio. In addition to the nebular lines, the spectra show prominent stellar absorption lines, such as $Ca\ II\ K$, G band, and $Mg\ b$.

3.1. Continuum Morphology

Figure 3 (left) shows in gray scale the I image of NGC 2110 in the PC. Out of the central $2''$, the red continuum distribution is very smooth and typical of an early-type galaxy, with the isophotes oriented along $P.A. = 160^\circ\text{--}170^\circ$. A mosaic image built combining the PC and the three WF cameras do not show any additional information about low surface brightness continuum in the outskirts of the galaxy, which could reflect any distortion of the morphology. However, in the circumnuclear region, NGC 2110 shows an asymmetry of its inner isophotes in the east-west direction due to the dust lanes that run north-south between $1''$ and $2''$ west of the nucleus and trace a clear spiral pattern around the nucleus. These dust-lane structures are shown more clearly in the unsharp-masked I image (Fig. 3, right). Nuclear spiral dust lanes are commonly found in *HST*

FIG. 3.—*HST*+WFPC2 (PC) images of NGC 2110. *Left*: The continuum emission through the filter F791W is in gray scale. Overplotted as solid lines are the isophotal contours fitted to this image. *Right*: Unsharp masked image. Dust lanes trace a spiral pattern around and to the nucleus, seen clearly at $1''$ and $2''$ to the west. [See the electronic edition of the *Journal* for a color version of this figure.]

observations of active galaxies (Regan & Mulchaey 1999; Martini & Pogge 1999; Pogge & Martini 2002). They would correspond to spiral arms formed in non-self-gravitating disk by hydrodynamic instabilities, and they could represent the paths of the gas infalling to the center of the galaxy. This image has been obtained by dividing the original *I* image by a 31 pixel median filtered version of the same image. However, the same structures are seen if the original *I* image is divided by the model obtained fitting ellipses to the continuum distribution (see below).

To constrain the photometric center, the position angle of the photometric major axis, and the inclination of the disk of NGC 2110, we have performed an isophotal fit to the *I* image using the IRAF task *ellipse* on the STSDAS analysis package. No constraints were imposed on the fits; thus, the resulting ellipses are all free in the different parameters (center, ellipticity, etc.). The fitted ellipses are shown over the gray-scale *I* image (Fig. 3, *left*). The major axis of the fitted ellipses defines the position angle of the photometric major axis position angle. This position angle is 163.5° from north to east. The inclination of the disk, obtained from the ellipticity of the isophotes, is 42° . Both values are in very good agreement with previously published values (Wilson & Baldwin 1985). To get the photometric center, we have calculated the difference between the center of each fitted ellipse and the location of the maximum of the *I* image. The median residuals are $0''.13$ in R.A. and $0''.07$ in decl. The largest difference come from the isophotes more affected by the dust lanes, while the outer isophotes give smaller residuals. Therefore, the isophotes indicate that the photometric center of the galaxy is indeed at the maximum of the *I*-band flux.

Figure 4 (*left*) presents the central emission through the filter F606W. It shows clearly the east-west asymmetry at $1''$ – $2''$ west of the nucleus due to the dust lanes. The inner $2''$ isophotes show a steeper gradient to the west. We have con-

volved this image with a Gaussian (Fig. 4, *middle*) to compare it visually with the IFS continuum images. Figure 4 (*right*) shows the continuum obtained from the observed IFS spectra after integrating the fluxes between 5320 and 5440 Å.

3.2. Ionized Gas Morphology

The *HST* $H\alpha$ continuum-free image is plotted in Figure 5 (*top left*). It shows a nuclear point source plus the circumnuclear emission extended along the north-south direction. It has a bright plume extended $1''$ from the nucleus to the north that is aligned with the radio jet. This plume is narrowest toward the nucleus. At $1''$ south, there are two $H\alpha$ clouds that may be related with the southern radio lobe. However, as it has been previously reported by Mulchaey et al. (1994), the $H\alpha$ brightness distribution of the plume and the two clouds appear to be anticorrelated with the maximum of the lobes of the radio jet. At larger scales, the $H\alpha$ emission shows an S-shaped distribution that extends $5''$ to the north and $4''$ to the south. The north side of the S-shaped ionized gas morphology follows the inner edge of the dust-lane distribution seen in the unsharp-masked *I* image (Fig. 6). However, at the south, the ionized gas is between the two dust lanes, but it does not follow so well the curve of the dust lane. Therefore, this large-scale ionized gas distribution could be reflecting the gas flows toward the nucleus that is photoionized by the AGN.

The emission-line maps of $H\beta$, [O III] $\lambda 5007$, [O I] $\lambda 6300$, $H\alpha$, [N II] $\lambda 6584$, and [S II] $\lambda\lambda 6717, 6732$ have been also obtained fitting a single-Gaussian profile to the corresponding nebular line in the IFS. Figure 5 compares the *HST* $H\alpha$ image convolved with a Gaussian with σ equal to the mean seeing with the IFS $H\alpha$ and $H\beta$. The extension of the emission and the morphology of the large-scale distribution are remarkably equal. However, the inner $1''$ gas distribution

FIG. 4.—*Left:* *HST*+WFPC2 image of the central light distribution of NGC 2110 through the filter F606W. *Middle:* F606W image convolved with a Gaussian with a $\sigma =$ mean seeing. *Right:* IFS image of the stellar light distribution in the central region of NGC 2110 traced by a continuum window centered at 5380 Å.

FIG. 5.—*Top left:* *HST* H α image. *Top right:* *HST*-H α image convolved with a Gaussian of FWHM equal to the mean seeing of our IFS data. *Bottom left:* IFS H α image. *Bottom right:* IFS H β image.

FIG. 6.—Unsharp-masked I image is plotted in gray scale. The contours correspond to the HST $H\alpha$ image.

seen in the HST $H\alpha$ image is lost in our ground-based observations owing to the seeing. Within an uncertainty of $0''.2$, the peak of the optical continuum is coincident with the maximum of the nebular lines.

As previously reported (Wilson et al. 1985; Pogge 1989; Mulchaey et al. 1994), the $[O\text{ III}]$ emission (Fig. 7) is more asymmetric than $H\alpha$; it is brightest at the north than at the south. The $[O\text{ III}]$ emission also extends more than $6''$ to the north; however, at the south, it does not show the larger scale S-shape emission detected in the $H\alpha$ and $H\beta$ emission. This high-excitation gas is aligned with the radio jet; however, there is not a one-to-one correspondence between the optical and the radio jet (Mulchaey et al. 1994). The $[O\text{ I}]$ $\lambda 6300$, $[N\text{ II}]$ $\lambda 6584$, and $[S\text{ II}]$ $\lambda\lambda 6717, 6732$ images also show an asymmetric morphology, more extended and brighter to the north than to the south. On the north, the emission lines show a similar distribution to $H\beta$ and $H\alpha$, but on the south, their morphology is more similar to the $[O\text{ III}]$ emission.

Excitation maps have been obtained by dividing the emission-line images of $[O\text{ III}]$ and $[N\text{ II}]$ by $H\beta$ and $H\alpha$, respectively. These ratios are plotted in Figure 8. There is a clear gradient in the $[O\text{ III}]/H\beta$ and $[N\text{ II}]/H\alpha$ ratios. Both images show the lowest ratio at the south, between $2''$ and $4''$ from the nucleus. The maximum of the $[O\text{ III}]/H\beta \sim 10$, occurs between $3''$ and $4''$ north of the nucleus. A maximum of the $[N\text{ II}]/H\alpha, \sim 1.6$, occurs near the nucleus.

3.3. Stellar Absorption Lines

In addition to the nebular lines, the circumnuclear spectra show prominent metallic absorption lines, such as Ca II at $\lambda 3933$, G band at $\lambda 4300$, and $\text{Mg } b$ $\lambda 5200$. To measure the strength of these absorption features, we have determined for each individual spectrum a pseudocontinuum in selected pivot wavelengths, and we have measured the equivalent widths integrating the fluxes under the pseudocontinuum in defined wavelength windows. We measure the Ca II K line in the window $3908\text{--}3952\text{ \AA}$ and the G band in the window $4284\text{--}4318\text{ \AA}$. The pivot wavelengths that we use are at $3780, 3810, 3910, 4015, 4140, 4260$, and $4430\text{ \AA}$. Once the equivalent widths are measured, the two-dimensional maps are obtained following the method described in § 2.3.

The spatial distribution of the equivalent widths of the metallic lines in the circumnuclear region allows us to estimate the possible variation of the stellar population as a function of the distance to the nucleus. Thus, relatively low values of the equivalent widths of these lines could be produced by the presence of a young stellar population. Alternatively, values of the equivalent widths lower than those expected by an old population at the nucleus and circumnuclear region can be caused by scattered light from the hidden Seyfert 1 nucleus.

Figure 9 shows the equivalent-width isocontours of the Ca II K absorption line. The contours are aligned with the

FIG. 7.—INTEGRAL images of the ionized gas circumnuclear region of NGC 2110 as traced by [O III] $\lambda 5007$ (top left), [O I] $\lambda 6300$ (top right), [N II] $\lambda 6584$ (bottom left), and [S II] $\lambda\lambda 6717, 6731$ (bottom right). The contours correspond to (a) 3, 5, 10, 15, 20, 40, 60, 80, 100, 150, 250, and 300×10^{-15} ergs s $^{-1}$ cm $^{-2}$; (b) 3, 5, 15, 25, 50, 75, and 100×10^{-15} ergs s $^{-1}$ cm $^{-2}$; (c) 3, 5, 10, 20, 30, 40, 50, 70, 100, 150, 200, 250, and 300×10^{-15} ergs s $^{-1}$ cm $^{-2}$; and (d) 3, 5, 10, 15, 25, 50, 75, and 100×10^{-15} ergs s $^{-1}$ cm $^{-2}$.

optical jet detected in the emission lines. The strength of this line and of the G band decreases inward. The minimum value of the Ca II equivalent width, ~ 11 Å, occurs nearby the nucleus and at $2''$ north, where there is also a maximum of the radio and optical jet. This spatial distribution suggests that extended scattered light from the nucleus could be responsible for the dilution of the strength of the metallic lines. Alternatively, as has been previously suggested (Cid Fernandes & Terlevich 1995; Cid Fernandes et al. 2001), the *featureless continuum* that dilutes the Ca II K line from the old stars in the host's bulge could be provided by a very young (few megayear old) stellar population.

4. IONIZED GAS AND STELLAR KINEMATICS

4.1. Velocity Field and Velocity Dispersion Map of the Ionized Gas

The velocity field was obtained by fitting a single-Gaussian profile to the emission lines ($H\beta$, [O III] $\lambda 5007$, $H\alpha$, [N II]

$\lambda 6584$, and [S II] $\lambda\lambda 6717, 6731$). Although the [O III] line profile shows evidence for kinematic substructure, the mean velocity field is well represented by the centroid wavelength of the brightest component. In fact, in the central $2''$, a blue weaker component is integrated along the line of sight. This blue component is not clearly detected in $H\alpha$, [N II], or [S II] in the IFS data, but kinematic structure is clearly detected in the KPNO data. This is due to a larger excitation of this second component with respect to the main one, combined with the lower spectral resolution of our IFS data.

We have defined the mean nuclear velocity of NGC 2110 as the velocity of the ionized gas in the region where the maximum of the continuum occurs. This velocity, estimated from the $H\beta$ and [N II] lines, 2315 km s $^{-1}$ (after correcting by the heliocentric velocity of -20 km s $^{-1}$), agrees well with the systemic velocity reported by Strauss et al. (1992), and it is 30 km s $^{-1}$ larger than the optical line velocity reported in the RC3 (de Vaucouleurs et al. 1991). It is also in agreement with the nuclear velocity reported by Wilson et al. (1985).

FIG. 8.—INTEGRAL images of the excitation of the ionized gas in the circumnuclear region of NGC 2110 as traced by [O III] $\lambda 5007$ /H β (left) and [N II] $\lambda 6584$ /H α (right). Contours correspond to (a) 1.5, 2.3, 4.5, 6.7, 8.9, 10, and 11; and (b) 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, 1.5, and 1.6. [See the electronic edition of the Journal for a color version of this figure.]

Figure 10 shows the velocity field of the ionized gas as traced by [N II] and [O III]. These maps clearly show a north-south asymmetry, with a larger velocity gradient in the south than in the north. In fact, over $5''$ from the optical nucleus along the major photometric axis, i.e., P.A. = 163° , the velocities change by about $+300 \text{ km s}^{-1}$ toward the

south and about -100 km s^{-1} toward the north (see also Fig. 11). Despite this result, the present velocity field does not support the possibility that the kinematic center of rotation is at $1''.7$ toward the south of the optical nucleus. In fact, the isovelocity lines crossing that point are clearly bent toward the redshifted side of the velocity field and away from the nucleus, far from the expected behavior for the kinematic minor axis. On the contrary, the isovelocity lines crossing the optical nucleus, although winding, do not show any preferred side, as expected for the true minor kinematic axis. This clear kinematic asymmetry along the major photometric axis, plus the nonuniform distribution of the blue velocity contours, suggests that the circumnuclear gas is not normally rotating ambient, interstellar gas in the disk of the galaxy, as was previously reported (Wilson et al. 1985).

To check the absolute velocity scale and the shape of the velocity field, we have compared the velocity curve obtained from our KPNO data with a cut on the INTEGRAL velocity field along P.A. = 6° (Fig. 12). We have fitted a Gaussian to the KPNO data except in the central $2''$, where two Gaussians give a better fit. However, in Figure 12 we have plotted only the velocities of the brightest component. The agreement in amplitude and absolute values between the two curves is very good. Therefore, we are confident about our estimation of the absolute values of the velocity field within uncertainties of 15 km s^{-1} .

The velocity dispersion of the gas has been estimated from the FWHM of the Gaussian profile fitted to the nebular lines. The INTEGRAL FWHM map has been transformed to a velocity dispersion map after correcting by the instrumental resolution. Owing to the variation in focus of the WYFFOS spectrograph as a function of the position on the detector, we have obtained an image with the FWHM of the arc line spectra measured over the 180 fibers. This image was subtracted quadratically from the FWHM of the emission-line images of NGC 2110.

FIG. 9.—Isocontours (solid line) of the equivalent width of the absorption line Ca II K measured in the individual spectra over the H β emission-line distribution (dotted line). The contours plotted have equivalent width of 11.2, 11.5, 12, 12.5, 13, and 13.5 Å. The equivalent width decreases inward, and the inner contour corresponds to 11.2 Å. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 10.—Velocity field of the ionized gas in the central region of NGC 2110 inferred from a single-Gaussian profile fit to the emission lines (a) [O III] $\lambda 5007$ and (b) [N II] $\lambda 6584$. Continuum light is also plotted by gray scale and by the dotted lines. Isovelocity lines are plotted in steps of 25 km s^{-1} . The dashed lines show velocity values below 2315 km s^{-1} , and solid lines show velocity values larger than 2315 km s^{-1} . The isovelocity contour of 2315 km s^{-1} is plotted by a solid white line. [See the electronic edition of the Journal for a color version of this figure.]

Figure 13 plots the sigma of the INTEGRAL velocity dispersion of the ionized gas traced by [O III] and [N II] over the photometric isophotes of the continuum at 5000 and 6600 Å, respectively. The velocity dispersion shows a barlike morphology oriented along P.A. = 60° – 70° , which is close to the photometric minor axis. The maximum of this sigma velocity dispersion, $\sigma = 230 \text{ km s}^{-1}$ for [N II] and 280–290

km s^{-1} for [O III] (Fig. 14), is coincident with the peak of the continuum. This result also suggests that the kinematic center is not shifted $1''.7$ to the south of the optical nucleus but that it is coincident with it. On the other hand, the alignment of the isodispersion velocity contours with the minor axis indicates that other nonrotational motions contribute to the kinematics of the circumnuclear ionized gas. Thus, this gas

FIG. 11.—Velocity curve of the ionized gas traced by H β (dotted line), [O III] (solid line) and [N II] (dashed line) obtained from cuts in the INTEGRAL velocity fields along the major (left) and minor (right) photometric angle. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 12.—Comparison of the velocity curve of the ionized gas obtained from the KPNO data (*cross*) and a cut on the IFS velocity field along P.A. = 6° (*line*). The velocity curve for [O III] is on the left, and that for [N II] is on the right. [See the electronic edition of the *Journal* for a color version of this figure.]

is not in pure rotational motion. This result has been observed in edge-on starbursts (Lehnert & Heckman 1996) and in some Seyfert galaxies (Colbert et al. 1996). In both cases, the off-nuclear emission-line widths are maximal along the galaxy minor axis. It is believed that it is due to a thermal wind driven by the starburst or the AGN.

4.2. Stellar Velocity Field and Velocity Dispersion

The stellar velocity curve and the velocity dispersion of NGC 2110 along P.A. = 6° has been inferred from the Ca II triplet ($\lambda\lambda 8498, 8542, 8662$) absorption lines via the cross-correlation method (Tonry & Davis 1979). We use the *fxcor* task of IRAF between the NGC 2110 spectra (8500–8800

FIG. 13.—Velocity dispersion of the ionized gas in the central region of NGC 2110 inferred from a single-Gaussian profile fit to the emission lines (a) [O III] $\lambda 5007$ and (b) [N II] $\lambda 6584$. Continuum light is also plotted by gray scale and by dotted lines. Isosigma velocity dispersion is plotted in steps of 20 km s^{-1} with the minimum contour of 100 km s^{-1} and the maximum contours of 340 and 240 km s^{-1} for [O III] and [N II], respectively. [See the electronic edition of the *Journal* for a color version of this figure.]

FIG. 14.—As Fig. 11, but for the ionized gas velocity dispersion. [See the electronic edition of the Journal for a color version of this figure.]

Å) and two K giant stars that were observed as velocity templates.

The shape of the velocity curve obtained with the two stars is very similar. However, the absolute values are shifted by 40 km s⁻¹. This shift is due to the zero velocity of each standard-velocity star being different. In fact, the Ca II lines are blueshifted with respect to the nominal wavelengths in the spectrum of one of the stars and redshifted by a similar amount (about 0.5 Å) in the other star. We take the mean stellar velocity curve. We estimate the systemic velocity as the velocity of the maximum of the continuum at 8500 Å. This velocity, 2380 km s⁻¹ (after correcting by the heliocentric velocity of -20 km s⁻¹), is equal to the velocity that we infer by symmetrizing the stellar velocity curve with respect to the nucleus. The amplitude of this curve is $\sim \pm 160$ km s⁻¹. Typical errors are ~ 30 km s⁻¹.

Figure 15 compares the stellar with the ionized gas (traced by [N II] measured in the IFS and H α measured in the KPNO data) velocity curves at P.A. = 6°. Note the asymmetry of the velocity curve of the ionized gas with respect to the nucleus, and the larger amplitude of this curve with respect to the stellar one. This plot also clearly shows that the ionized nuclear gas is blueshifted with respect to the stellar systemic velocity. However, [O III] nuclear emission blueshifted with respect to the stellar motions is commonplace in Seyfert nuclei (e.g., Nelson & Whittle 1995).

The stellar velocity dispersion along P.A. = 6° has been also estimated from the width of the cross-correlation function. Like the velocity dispersion of the ionized gas, the radial distribution of the velocity dispersion also peaks at the position of the nucleus. The stellar velocity dispersion of the nucleus is $\sigma = 260 \pm 20$ km s⁻¹, in agreement with the value ($\sigma = 220 \pm 25$ km s⁻¹) estimated by Nelson & Whittle (1995) using the Mg b lines.

4.3. Kinematics of the Nuclear Ionized Gas

The kinematics of the ionized gas in the central 2'' is complex. The [O III] line shows a very asymmetric profile with a blue wing that extends up to 2'' to the south from the continuum peak. This result was previously reported by Wilson et al. (1985). This kinematic structure is fainter in H β , but is

FIG. 15.—Comparison of the stellar velocity curve (stars) along the P.A. = 6° inferred from the cross-correlation in the spectral range of the Ca II triplet with the velocity curve of the ionized gas traced by the emission-line [N II] (dashed line) inferred from a cut in the velocity field map (Fig. 7a) along P.A. = 6° and the velocity curve of H α (dots and circled dots) obtained from the KPNO data. The circled dots represent the two kinematic components fitted to the H α line. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 16.—Profile of the $H\alpha$, and $[N\text{ II}]\lambda\lambda 6548, 6584$ lines in the KPNO data for the cross section where the continuum is maximum (nucleus) and the three next cross sections to the south. The spatial sampling is $0''.7$ pixel $^{-1}$. The difference in velocity between the two components is about 250 km s^{-1} . [See the electronic edition of the *Journal* for a color version of this figure.]

also detected in our KPNO data in the $H\alpha$, $[N\text{ II}]$, and $[S\text{ II}]$ lines. At the nucleus (the maximum of the continuum), $H\alpha$ and $[N\text{ II}]$ show two velocity components, with the weaker component at redder wavelengths than the brighter one. However, at $2''$ south of the nucleus, the weaker component is at bluer wavelengths (Fig. 16). We have fitted two Gaussians to each line ($H\alpha$ and $[N\text{ II}]\lambda\lambda 6584, 6548$) to fit the whole profile, and we find that the difference in velocity between these two kinematic components is 250 km s^{-1} . We have plotted these two values in the $H\alpha$ velocity curve (Fig. 15) as circled dots. Note that these components are blue- and redshifted with respect to their corresponding radial stellar velocity, suggesting that the central ionized gas is an expanding jet or bubble-like kinematic structure, thus implying that the central gas is outflowing. This outflow could be caused by the interaction of the radio jet with the circumnuclear gas.

We have visually inspected some $[O\text{ III}]$ and $H\alpha + [N\text{ II}]$ high-resolution STIS spectra (gratings G430M and G750M) that are available in the *HST* archive (PIs M. Whittle and C. G. Mundell, respectively). Both data sets have been taken close to the kinematic major axis with a slit width of $0''.2$. These spectra corroborate our results, but they also show that the kinematics of the ionized gas at $0''.1$ scales is even more complex in detail than provided by the data we present here.

5. DISCUSSION

5.1. Evidence for Nonrotational Motions in NGC 2110

The ionized gas velocity field in NGC 2110 was obtained by Wilson & Baldwin (1985) on the basis of long-slit spectroscopic observations. They reported a pattern remarkably similar to the rotation curves commonly obtained for spiral galaxies, suggesting that the ionized gas in NGC 2110 was indicating rotation. However, they also reported an interesting asymmetry. Taking the nucleus as reference, the velocities increase more rapidly to the south than to the north.

This result led them to suggest that the true kinematic center (i.e., center of rotation) was $1''.7 \pm 0''.4$ toward the south of the optical nucleus. They proposed several alternatives to explain the offset of the kinematic center: (1) dust obscuration that hides the true continuum nucleus, (2) the ionized gas is not in gravitational motion, or (3) stars and gas are orbiting in a gravitational potential of a large amount of obscured or dark matter. They dismissed hypothesis 1 because the outer isophotes of the stellar light are not centered on their estimation of the kinematic center. Arguments against hypothesis 2 and in favor of 3 are the description of their velocity curve in terms of a rotation disk. However, for hypothesis 3 to be correct, the interior mass of the nucleus should be $\sim 8 \times 10^9 M_\odot$, which is too large to not leave a strong signature on the stellar light isophotes. Therefore, they did not find any satisfactory interpretation for the velocity field. Our results indicate that the kinematic center of NGC 2110 is not offset with respect to the optical nucleus, and their hypothesis 2 is correct, as we have shown in § 4 and as we further discuss below.

The most clear indication that the warm gas is not just rotating under the galaxy gravitational potential comes from the comparison between its velocity and the stellar velocity along the P.A. = 6° (Fig. 15). From this figure we infer that (1) the nucleus is indeed at a symmetric position with respect to the stellar kinematics and (2) the amplitude of the ionized gas velocity curve is larger by $70\text{--}90\text{ km s}^{-1}$ than the corresponding to the stellar curve. The ionized gas kinematics also support this result. Figures 10 and 13 show the velocity field and the velocity dispersion over NGC 2110 as derived from Gaussian fits to the $H\alpha$ and $[N\text{ II}]$ emission lines. These maps clearly show the asymmetry reported by Wilson & Baldwin (1985). However, they reveal some features that do not suggest rotation. The asymmetry between the north and south regions of the velocity field is deeper than just the asymmetry in the rotation curve. In the red part the maximum is clearly defined at about $4''$. It is slightly (but significantly) offset from the major photometric axis. The highest velocities in the blue part (north) are found in two regions, each at one side of the photometric major axis. In addition, everywhere in the receding part of the velocity field the velocities change more rapidly than in the corresponding blue region. Moreover, the amplitude of this velocity field ($\sim 400\text{ km s}^{-1}$) is very large if compared with what is typical for early-type galaxies (see, for instance, Simien & Prugniel 2000). In addition, the gas velocity dispersion map is elongated along the minor photometric angle, which presumably points to the rotation axis of the galaxy. All this suggests that the motions of the ionized gas do not indicate gravitationally bound orbits, as previously suggested.

To quantify the differences between the ionized gas velocity field with respect to a pure rotation disk, we have built a two-dimensional rotational model using a one-dimensional model fitted to the stellar velocity field. We use equation (2-54c) of Binney & Tremaine (1987):

$$v_c = \frac{v_0 r}{\sqrt{r^2 + r_0^2}}, \quad (1)$$

where v_0 is the asymptotic rotational velocity and r_0 the distance from the kinematic center at which the velocity arises to $v_0/\sqrt{2}$. From a fit to the deprojected stellar velocity curve, we obtain the values of $v_0 = 245\text{ km s}^{-1}$ and $r_0 = 1.85''$. With these parameters we have built the two-dimensional

rotational model, projected to the plane of the sky with an inclination of 42° , the line of nodes at P.A. = 163° and a systemic velocity equal to 2380 km s^{-1} (as determined by the stellar rotational curve). The predicted velocity field and the residual map resulting from the subtraction of this rotational disk to the IFS velocity field are plotted in Figure 17. The residual map shows that the nucleus is blueshifted with respect to the systemic velocity, and there is an excess velocity of up to $+100 \text{ km s}^{-1}$ on the south. The residuals on the north are smaller, less than 30 km s^{-1} . Therefore, we have found strong evidence that the ionized gas in the south of NGC 2110 is not following the pure gravitational potential of the galaxy.

5.2. Origin of the Outflowing Nuclear Ionized Gas

The residual velocity map and the kinematic structure found in the strongest nebular lines and the two velocity components in $\text{H}\alpha$ and $[\text{N II}]$ indicate that the narrow-line region (NLR) gas is flowing out of NGC 2110. Additional evidence of an outflowing gas is the alignment of the maximum of the emission-line widths and the galaxy minor axis. Other examples of outflows in AGNs have been reported previously. In some cases the outflow is spatially resolved at large scales (e.g., Cecil, Bland, & Tully 1990; Colbert et al. 1996; Veilleux, Shopbell, & Miller 2001; Arribas, Colina, & Clements 2001), and in other cases the outflow is not resolved and is restricted to the NLR (e.g., Whittle 1985). Several mechanisms can be responsible for the outflow. They are (1) a thermal wind from a circumnuclear starburst (e.g., Colina et al. 1999), (2) a thermal wind by the AGN torus (Krolik & Begelman 1986), and (3) collimation by a radio jet (Taylor, Dyson, & Axon 1992) or entrainment along the radio jet.

We can discard the circumnuclear starburst model as the origin of the outflow in NGC 2110 based on our previous analysis of the nuclear stellar population. The optical continuum distribution and the stellar features do not show any strong evidence of a circumnuclear starburst, except that a small fraction of the optical light could be provided by a young stellar population or by a scattered light from the hidden Seyfert 1 nucleus. Because of the degeneracy in the slope between a power law and a young ($\leq 10 \text{ Myr}$) stellar population (see Cid Fernandes & Terlevich 1995), we cannot distinguish between these two components. The analysis of the equivalent width of the stellar features (Ca II K and G band) presented here (see Fig. 9) also indicates that the scattered light (or the young stellar component) has to be extended toward the north of the nucleus. However, in the absence of a strong evidence for the existence of a starburst, such as Wolf-Rayet features, high-order Balmer lines in absorption, etc., we interpret this dilution as produced by AGN scattered light.

A detailed analysis of the STIS spectra should distinguish between the other three mechanisms. However, our analysis and the radio morphology of NGC 2110 points out to the collimated jet-driven outflow model as the more plausible mechanism for the nuclear outflow. The radio continuum observations (Ulvestad & Wilson 1983; Nagar et al. 1999) have revealed a linear radio structure aligned $\pm 2''$ north-south from the nucleus. Mulchaey et al. (1994) have found that the optical emission lines and radio continuum emission extend along similar directions; however, their brightness distributions appear anticorrelated, and the optical jet is more curved than the radio jet. Pringle et al. (1999) have derived the orientation of the radio jet. They found that the jet is at 50° from the line of sight and 29° with respect to the

FIG. 17.—(a) Two-dimensional rotational model built with the stellar velocity curve and projected to the plane of the sky at 42° inclination. The P.A. of the line of nodes is 163.5° and the systemic velocity is 2380 km s^{-1} . (b) Residual velocity map resulting from the subtraction of the disk rotational model from the ionized velocity gas traced by the $[\text{N II}]$ emission line. The contours are plotted in steps of 10 km s^{-1} . Dashed contours go from -80 to -10 km s^{-1} , and the solid contours from 10 to 100 km s^{-1} . [See the electronic edition of the *Journal* for a color version of this figure.]

line of nodes. Therefore, the radio jet is not parallel to the rotational axis. This misalignment suggests that the angular momentum vector of the accretion disk collimating the jet is also misaligned with respect to the host galaxy. However, these angles indicate that the radio jet is pointing toward us, and therefore it explains the blueshifted velocities observed in the nuclear region as due to a jet-induced outflow.

5.3. Origin of the Nonrotational Motions on the South of the Galaxy

Figure 15 indicates that, excluding the nucleus, the stellar and ionized gas velocities fields are in very good agreement toward the north. Toward the south, the disagreement is clear, although the residual velocities (Fig. 17, *right*) do not correlate with the ionized gas distribution (Fig. 5). Therefore, although the radio jet may play a role to explain the north-south asymmetry in the velocity field of the ionized gas, another mechanism is required to explain why the ionized gas is redshifted by more than about 100 km s^{-1} with respect to the stellar rotation velocity field at the south of the galaxy and about 240 km s^{-1} with respect to the nuclear stellar velocity.

Other evidence that the velocity field at the south is peculiar has been reported by Gallimore et al. (1999). H I observations with the VLA have detected an H I cloud in absorption, located south of the maximum of the radio continuum emission. This cloud has a velocity of 2626 km s^{-1} and, therefore, it is redshifted about 246 km s^{-1} with respect to the nuclear stellar systemic velocity. Gallimore et al. have interpreted this H I absorption as a rotational disk of H I. They argue that we may not see the H I disk in the north because the north radio jet is in front of the disk as seen by us; at the south, the radio jet is behind the disk illuminating it. However, this H I velocity agrees very well with the velocity of the ionized gas that we measure at the south of the galaxy, both thus having an excess $+100 \text{ km s}^{-1}$ with respect to the pure rotation at that radius. Therefore, an alternative explanation is that an H I cloud is infalling toward the galaxy and it is impacting close to the center of NGC 2110.

The decoupling between the ionized gas and the stellar velocities could be explained if a minor merger is occurring in NGC 2110. The fact that the morphology at large scales is not perturbed (we do not see distortion of the isophotal contours or evidence of tidal tails) indicates that it would have to be a minor merger with a small galaxy or an intergalactic H I cloud that does not produce a strong effect on the large-scale morphology of the galaxy. This is supported by previous studies of the effects of a minor merger in a main galaxy. From a detailed study of a sample of nearby Sa galaxies, Haynes et al. (2000) and Haynes (2001) find that while these galaxies show no morphological signs of interaction, they do show a range of clear kinematical peculiarities that can be interpreted in terms of a kinematic memory of a past minor merger. A similar conclusion has also been reached by numerical simulations of minor merger accretion by early-type galaxies (Bak 2000); Bak concludes that there is no major photometric distinction between galaxies that have undergone a minor merger and those that have not.

To investigate the minor-merger hypothesis as the origin of the redshifted H I absorption line and the excess of the ionized gas redshifted velocity at the south of the nucleus, we have further inspected the *HST* images to look for fine detail morphological peculiarities in the center of the gal-

axy. An unsharp-masked F606W image (Fig. 18) reveals some morphological features that have not been detected previously in the *I* and H α images. Besides the dust lanes that trace a spiral pattern toward the nucleus that are common in *HST* images of galaxies (e.g., Pogge & Martini 2002), there are some residual arcs in emission at a radius of $6''$ – $8''$ located south to northeast to north of the nucleus. In addition, there are also some *radial* dust lanes. Note that while the more typical spiraling dust lanes are located mostly to the northwest side (and south at small radii), these *radial* dust lanes are mostly located at the southeast to southwest quadrants (at larger radii), in particular, the most prominent of these lanes is at the southwest pointing directly to the H I cloud.

These features are very faint, and they do not affect the large-scale symmetry in the isophotal analysis, in agreement with the findings of Haynes (2001) and Bak (2000). A possible interpretation is that these faint features and kinematic peculiarities in the south of the galaxy are produced by a minor merger with a small satellite or intergalactic H I cloud that passed through in a highly inclined orbit close to the nucleus of NGC 2110. Merger or passage of larger satellite galaxies do produce similar spokelike structures, but at significantly larger scales, that are very clearly reflected on the overall morphology of the galaxy (such as, e.g., the Cartwheel). Very detailed analysis of faint structures is needed to find more such little mass encounter candidates.

Thus, if the interpretation of these morphological and kinematic peculiarities is correct, we are observing a case in which the nuclear activity could be driven by a minor merger. Taniguchi (1999) has proposed that the fueling mechanism of isolated nonbarred Seyfert galaxies could be due to a minor merger between a disk galaxy and a nucleated satellite. If the major galaxy has a gas-poor disk, then Seyfert activity without circumnuclear star formation is triggered. Even more, he suggests that the plane of the accretion disk that forms is parallel to the galaxy rotation disk if the satellite impacts the disk with an almost aligned orbit. On the contrary, when the satellite impacts almost perpendicular to the disk, a Seyfert 2 can form with the plane of the accretion disk highly inclined with respect to the rotational disk of the host galaxy. This scenario gives also a plausible explanation for the misalignment between the orientation of the radio jet and the galaxy rotation axis of NGC 2110.

Thus, we suggest that the morphological and kinematic peculiarities seen in the south of NGC 2110 could be produced by a minor merger of the galaxy with a nucleated satellite that impacts the disk of NGC 2110 close to its nucleus with a highly inclined orbit. We speculate that this could be the mechanism responsible for triggering the Seyfert activity in this isolated nonbarred Sa galaxy and driving the gas toward the center to feed the AGN.

6. SUMMARY AND CONCLUSIONS

We have obtained integral field optical spectroscopy in the range 3700 – $7000 \text{ \AA}$ and long-slit optical spectroscopy (3400 – 5500 and 6600 – $9100 \text{ \AA}$) along P.A. = 6° of the Seyfert 2 galaxy NGC 2110. These observations allow us to get the distributions of the emission lines (H α , H β , [O III], [O I], [N II], and [S II]), the ionized gas velocity field, the velocity dispersion map, and the stellar velocity curve along

FIG. 18.—Unsharp-masked image of NGC 2110 obtained dividing the *HST*+WFPC2 image through the filter F606W by a median filtered version of the same image (*gray scale*). The H I absorption cloud detected by Gallimore et al. (1999) is plotted as an ellipse.

P.A. = 6° . These data combined with *HST*+WFPC2 (*I*, F606W, and $H\alpha$) have yielded the following results:

1. At large scales, the morphology of NGC 2110 is not perturbed. The red continuum is well fitted by ellipses that have their major axis oriented at P.A. = 163.5° and an inclination of 42° . The centers of these ellipses are located at the maximum of the continuum within $0''.13$ in R.A. and $0''.07$ in decl. This result indicates that the photometric center is at the nucleus of the galaxy.

2. *V* and *I* unsharp-masked images have revealed dust lanes that spiral toward the nucleus, and they may represent the gas flows that feed the AGN. The *V* (F606W) unsharp-masked image shows also radial dust lanes and emission arcs at $5''$ and $8''$ at the south and northeast, similar to the tidal debris predicted by numerical simulations of the merger of a small galaxy with a galaxy disk.

3. The ionized gas is extended in the north-south direction, such as the linear radio jet. The morphology of [O I], [N II], and [S II] is similar to [O III], that is more extended to the north than to the south. This distribution suggests that the gas at the north may be photoionized by the AGN. At larger scales, $H\alpha$ and $H\beta$ images show an S-shape that is similarly extended at the north and at the south.

4. The ionized velocity field shows clearly a north-south asymmetry, with a larger velocity gradient in the south than in the north. This asymmetry is seen also along the kinematic major axis. This result suggests that the ionized gas is

not normally rotating gas in the disk of the galaxy. The ionized [N II] nuclear gas velocity is 2315 km s^{-1} .

5. The ionized gas velocity dispersion map shows a bar-like morphology oriented near the photometric minor axis. The maximum of the velocity dispersion is also coincident with the maximum of the optical continuum. Thus, the kinematic center is coincident with the nucleus of NGC 2110. This alignment between the maximum of the emission-line widths and the galaxy minor axis may be due to a wind driven by the AGN.

6. The stellar velocity curve inferred from the Ca II triplet observed along P.A. = 6° is symmetric with respect to the nucleus that has a systemic velocity of 2380 km s^{-1} . The amplitude of the stellar velocity curve is lower than the amplitude of the ionized gas velocity curve.

7. The nuclear ionized gas of NGC 2110 is blueshifted with respect to the stellar systemic velocity. Two velocity components that are shifted $\pm 125 \text{ km s}^{-1}$ from the stellar rotation curve have been detected at the central $2''$. These components indicate that the NLR is outflowing, possibly driven by the radio jet.

8. At larger spatial scales (up to $5''$), the ionized gas on the south of NGC 2110 is redshifted by about 100 km s^{-1} with respect to the stellar velocity field and 240 km s^{-1} with respect to the nuclear stellar systemic velocity. This excess of the velocity with respect to the rotation indicates that the gas in the south of NGC 2110 is not following the pure gravitational potential of the galaxy. It is coincident with the H I

redshifted (240 km s^{-1}) absorption extended to the south of the nucleus detected by Gallimore et al. (1999).

We conclude that the ionized gas on the south is kinematically perturbed. This conclusion together with the morphological peculiarities detected (arcs, radial dust lanes) suggests that the nuclear activity could be the result of a minor merger. The collision with a nucleated small satellite (or with an intergalactic H I cloud) with a very high inclined orbit that impacts close to the nucleus may be responsible of the redshifted velocity of the ionized gas in the south of the galaxy and the arcs and radial dust lanes observed in the central host disk of the galaxy. This interpretation of the data is of relevance in relation with the fueling mechanism and the triggering of nuclear activity in isolated nonbarred Seyfert galaxies.

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