TWO-DIMENSIONAL KINEMATICAL AND IONIZATION STRUCTURE OF THE WARM GAS IN THE NUCLEAR REGIONS OF ARP 220

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ABSTRACT

Integral field optical spectroscopy using the INTEGRAL system has been used to characterize the kinematic and ionization properties of the warm gas within 2 kpc of the dust-enshrouded nucleus of Arp 220. Owing to the large internal extinction toward the nuclei, the brightest stellar and line-emitting regions observed at optical wavelengths do not coincide with the dust-enshrouded near-infrared and radio nuclei of Arp 220 but are located northwest of the nucleus at a distance of about 750 pc. Moreover, although the continuum and the line-emitting gas share similar distributions, their emission peaks are displaced, with the H α emission peak located at about 300 pc southwest of the optical stellar continuum emission peak. A line decomposition analysis has been performed in the complex and high spatially variable emission-line profiles. Three different kinematically distinct and extended gaseous components have been identified in the ionized gas. One narrow component (R) indicates rotation, while the other two components (O and B) are well interpreted by the presence of a biconical outflow. Specifically, the rotational component R traces quiescent gas located in a nuclear disk with the spin axis along the southeast-northwest direction (P.A. 135°). This component of ionized gas seems to be coupled with the 100 kpc disklike H I gas and the 1 kpc molecular disk detected in CO (Scoville et al.). The inclination-corrected rotational velocities imply a dynamical mass (M_{dyn}) of $2 \times 10^{10} M_{\odot}$ within a radius of 1.5 kpc. This relatively high value indicates a large mass concentration in the nuclear region of Arp 220, as Scoville et al. already inferred by the presence of $5 \times 10^9 M_{\odot}$ of molecular gas in a nuclear, 0.5 kpc disk. One of the outflow components, O, has peak-to-peak velocities of 1000 km s⁻¹. The broad component B, with an average width of 815 km s⁻¹, is detected at about 600 pc northwest of the dust-enshrouded nucleus and is blueshifted by 300 km s⁻¹ with respect to the system velocity. The two-dimensional distribution and kinematics of the components are consistent with a bipolar cone geometry with an opening angle of about 90° and are perpendicular to the nuclear disk of gas, as expected in the starburst-driven galactic wind scenario proposed by Heckman, Armus, & Miley. In most of the observed regions, the ionization status of the different gas components is consistent with a shock-heated LINER-like or Seyfert 2 nebula as judged by the [N II]/H α and [S II]/H α emission-line ratios. Although the [O III] and H β lines are undetected in most of the regions, the brightest zone located northwest of the nucleus could be classified as a Seyfert 2 nebula based on the additional constraint given by the measured lower limit (≥ 5) for the [O III]/H β ratio. There is no evidence of excitation gradients along the symmetry axis of the outflow nor of a biconical ionization structure, which suggests that the ionizing field is homogeneous and less collimated than the gas outflow. However, there are four clearly identified extranuclear regions where the [N II]/H α ratio decreases by a factor of 5 and is close to the typical values of H II regions. None of these regions are in spatial agreement with the star clusters found in the infrared by Scoville et al., confirming that they must be relatively old globular clusters.

Subject headings: galaxies: active — galaxies: individual (Arp 220) — galaxies: interactions — galaxies: nuclei — galaxies: starburst

1. INTRODUCTION

Arp 220 is the prototypical cool (i.e., $f_{25}/f_{60} < 0.2$) ultra-luminous infrared galaxy (ULIRG) with $L_{\text{IR}}(8\text{--}1000 \mu\text{m}) = 1.45 \times 10^{12} L_{\odot}$. Arp 220 is also the nearest ULIRG with a redshift of 0.01813 and is thus an ideal laboratory to study the processes taking place in ULIRGs.

Arp 220 shows clear signs of being at the final stage of a merging process. Optical images reveal extended tidal tails (Arp 1966; Surace, Sanders, & Evans 2000), and high-

resolution near-infrared and radio imaging shows the presence of two nuclei separated by 0''.98 (Carico et al. 1990; Graham et al. 1990; Baan & Haschick 1995; Scoville et al. 2000 and references therein). Moreover, Arp 220 is also extraordinarily rich in gas, with about $5 \times 10^9 M_{\odot}$ of molecular gas (M_{H_2}) concentrated in a thin nuclear disk with a radius of 250 pc (Scoville, Yun, & Bryant 1997).

The stellar and the cold gas components have been studied in detail (see Scoville et al. 1997; Sakamoto et al. 1999; Hibbard, Vacca, & Yun 2000; Surace et al. 2000 and references therein). The two near-infrared/molecular nuclei and their associated disks—which rotate in opposite directions—are embedded in a 1 kpc scale molecular disk, which rotates in the same sense as the 100 kpc scale H I disk (and one of the two nuclei), suggesting a prograde-retrograde encounter of two gas-rich spiral galaxies.

The ionized gas component in the nuclear regions of Arp 220 has been studied on the basis of long-slit observations

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FIG. 1.—Spatial distribution of the spectra in the spectral range 6630–6760 Å

along two position angles (see Heckman, Armus, & Miley 1990 and references therein). This study detected the presence of broad double-peaked emission lines separated by about 450 km s^{-1} that were interpreted as indicative of an expanding bubble within the starburst-driven superwind scenario (Heckman et al. 1990).

However, a detailed study of the flows present in the extended ionized gas of Arp 220 and how they are affected by the interaction process and massive nuclear starbursts requires an observational technique able to obtain two-dimensional velocity fields and ionization maps of the complex ionized gas structures detected in this galaxy. Integral field fiber spectroscopy (e.g., Arribas & Mediavilla 2000) is an ideal technique for such a study since it allows simultaneous and complete mapping of both the kinematic and ionization properties of the warm ionized gas. We have recently initiated a program to combine integral field spectroscopy data with *Hubble Space Telescope* (HST) imaging for a representative sample of low-redshift ULIRGs, covering the different evolutionary phases of the merging process and including candidates to multiple mergers (Borne et al. 2000). The first results of this program for Mrk 273, IRAS 12112+0305, and IRAS 08572+3915 have already been presented (Colina, Arribas, & Borne 1999; Colina et al. 2000; Arribas, Colina, & Borne 2000).

This paper presents the first two-dimensional study of the ionized gas in the central $6 \times 4.5 \text{ kpc}^2$ region of Arp 220. We will mainly discuss its distribution and kinematics. Several kinematically distinct gas components have been identified; their properties, locations, ionization status, and

connection with the dust-enshrouded nuclei will be discussed individually as well as globally in the framework of current scenarios. Throughout the paper, a distance of 77.6 Mpc is assumed for Arp 220 using a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. At the assumed distance, $1''$ corresponds to 375 pc.

2. OBSERVATIONS AND DATA REDUCTION

Integral field spectroscopy of Arp 220 was obtained with the INTEGRAL system (Arribas et al. 1998) and the Wide Field Fiber Optic Spectrograph (Bingham et al. 1994) on the 4.2 m William Herschel Telescope during 2000 May 7 and 8. We used the bundle of fibers “standard bundle 2,” which consists of 219 fibers (each $0.9''$ in diameter) covering a $16.5'' \times 12.3''$ field of view. The spectra were taken using a $1200 \text{ line mm}^{-1}$ grating, with an effective resolution of about 2.5 Å and covering the 6000–7400 Å spectral range. The total integration time was 9000 s, split into six separate integrations of 1500 s each, with seeing of about $1.2''$ and nonphotometric conditions. Spectra covering the 4700–6800 Å wavelength range were also taken during the second night. Because of the strong internal absorption in the nuclear region of Arp 220, only the [O III] lines were barely detected in a few spectra after a total 4500 s exposure time.

Data reduction followed the standard procedures applied to spectra obtained with two-dimensional fiber spectrographs (Arribas et al. 1997 and references therein), which basically consist of two main steps: (1) basic reduction of the spectra (i.e., biasing, flat-fielding, wavelength calibration, etc.) and (2) generation of maps of spectral features

(e.g., line intensity, velocity fields) from the spectra. Step 1 was performed inside the IRAF environment, and standard two-dimensional spectroscopy calibration routines were applied. For step 2 we used a Renka & Cline two-dimensional interpolation method to transform a file with the actual position of the fibers and the spectral feature (i.e., line emission, continuum within a window, radial velocity, line width, etc.) into a regularly spaced rectangular grid. In this way we built up images that could be treated with standard astronomical software. The two-dimensional distribution of the reduced spectra in the range of the redshifted $H\alpha$ + $[N II]$ lines (i.e., 6630–6760 Å) is presented in Figure 1. The changes in the profiles of the lines and in the ionization conditions (i.e., $H\alpha/[N II]$) are obvious from this figure alone.

3. RESULTS AND DISCUSSION

3.1. Stellar and Ionized Gas Distributions

The reduced spectra can be used to generate continuum and emission-line images following the procedures outlined

in § 2. In Figure 2 we present the images generated in this manner for a red narrow-continuum window (6425–6440 Å), $H\alpha$, and $[S II]$ 6716, 6731 Å emission lines, together with the archival Wide Field Planetary Camera 2 (WFPC2) *I*-band image of Arp 220.

In spite of its different wavelength range and poorer spatial resolution, the red continuum image reconstructed from the INTEGRAL data has a good correspondence with the WFPC2 *I*-band image. Since the brightest near-infrared emission peak, associated with the western nucleus (source W in Scoville et al. 1998), can be well identified in the WFPC2 *I*-band image, the location of this nucleus in the INTEGRAL continuum image (and therefore in *all* INTEGRAL images) can be fixed within an accuracy of better than 0".3. We have fixed the origin of coordinates of the INTEGRAL images at the location of the western infrared nucleus, whose absolute coordinates are $\alpha(1950) = 15^h32^m46^s.90$ and $\delta(1950) = +23^\circ41'07''.94$ (Scoville et al. 1998). It is clear that at optical wavelengths the continuum maximum is not associated with the near-infrared nucleus, which is under an extinction of about 13–17 mag in the

FIG. 2.—INTEGRAL images of the ionized gas and stellar light distribution in the central regions of Arp 220 as traced by different emission lines and by a continuum window (6425–6440 Å). Archival high-resolution *HST* *I*-band image (Surace et al. 1998) is also shown for comparison.

visual (Scoville et al. 1998), but with the bright extended structure (the northwest complex hereafter) located at about $2''$ (i.e., 750 pc) northwest of the dust-enshrouded nucleus.

Similarly, the $H\alpha$ and $[S\ II]$ emission-line images do not have their maxima associated with the infrared nucleus but rather with the northwest complex. The $H\alpha$ -emitting gas is well concentrated in this region, with a faint tail of emission toward the southeast and with a faint region located at about $6''$ northeast (P.A. 75°) from the nucleus.

The $[S\ II]$ emitting gas is more extended and its structure is closely related to that of the optical continuum. It is worth mentioning that although the northwestern optical stellar and ionized gas distributions are very similar, their emission does not peak at the same position. The $H\alpha$ emission peak is located about $0''.8$ (i.e., 300 pc) southwest (P.A. 225°) from the stellar emission peak (see Fig. 2).

None of the unresolved clusters identified in the near-infrared (Scoville et al. 1998), of which all but one are also detected in the I -band image, have associated local maxima in $H\alpha$ emission. This indicates that no massive young ionizing stars are present in these clusters. Previous near-infrared colors identified these clusters as old globular clusters with ages of at least 10^9 yr (Scoville et al. 1998), which is consistent with our findings.

3.2. Overall Kinematic Properties of the Ionized Gas

The line profiles presented in Figure 1 show clear evidence for substructure, indicating that the lines from several kinematically distinct gaseous components are integrated along the line of sight. In § 3.3 a decomposition of the line profiles will be performed, identifying the various velocity components, their spatial distribution, and their ionization status. However, before that, it is interesting to analyze the overall kinematic properties of the extended ionized nebula. To this aim, a single Gaussian profile has been fitted to the bright $[N\ II]\ 6583\ \text{\AA}$ line, even when the presence of more than one component is clear from the line profiles. From the results of these fits, the associated line-width and velocity field maps have been generated (Fig. 3). The velocity field is derived from the centroid wavelength of the line and therefore represents the velocity distribution of the dominant emission-line component. The two-dimensional map of the line width, traced by the full width at half-maximum (FWHM) of the single Gaussian fit, gives an idea of the complexity of the velocity structure as a function of position, whether this is due to several distinct kinematic components spread over a wide velocity range or to intrinsically broad emission line components.

The systemic velocity (cz) of Arp 220 defined, as the velocity of the ionized gas (i.e., $[N\ II]$) located in the region of the dust-enshrouded nucleus, is $5400 \pm 20\ \text{km s}^{-1}$. This velocity agrees with the $H\ I\ 21\ \text{cm}$ velocity ($5434 \pm 7\ \text{km s}^{-1}$; de Vaucouleurs et al. 1991) but is blueshifted by $111\ \text{km s}^{-1}$ with respect to the systemic velocity of $5511\ \text{km s}^{-1}$ derived from the velocity field of the nuclear molecular gas distribution (Scoville et al. 1997).

The overall velocity field has a rather regular pattern with receding velocities toward the northeast, approaching velocities toward the south and southwest, and a peak-to-peak amplitude of about $500\ \text{km s}^{-1}$. This pattern can be interpreted as rotating gas with the minor axis along a position angle of 135° (see discussion in § 3.4).

The northwest complex is the region showing the widest emission lines with velocities between 670 and $900\ \text{km s}^{-1}$

FIG. 3.—Line-width and velocity maps inferred from single-Gaussian fitting of the spectra.

(FWHM). The southeast complex also shows broad emission line profiles with velocities of up to $700\ \text{km s}^{-1}$ (FWHM). These large values may indicate not only the presence of intrinsically wide lines but also the presence of several kinematically distinct components spanning a wide range in relative velocities. Interestingly enough, the emission lines toward the direction of the dust-enshrouded infrared nuclei are relatively narrow ($\sim 300\ \text{km s}^{-1}$), which is a clear indication of the strong extinction in these regions. Lines are also narrow ($\sim 270\ \text{km s}^{-1}$) outside the region delineated by the northwest and southeast complexes, suggesting that gas in these regions is more undisturbed ambient gas and may be close to being quiescent. This is consistent with the idea of a rotating gas disk almost unaffected by the radial flows associated with the nuclear starbursts or by the tidal motions induced during the merging process.

The region with the widest emission line is located $2''.4$ northwest (P.A. 322°) of the western near-infrared nucleus (i.e., the origin of coordinates in all maps presented in this paper) and displaced by about $1''$ with respect to the emission peaks of the stellar and ionized gas components of the northwest complex. Moreover, the emission peak positions of the stellar and ionized gas components, together with the region with the widest emission lines, define the vertices of a $1''$ (i.e., 375 pc) per side equilateral triangle.

3.3. Kinematics and Ionization of the Distinct Ionized Gas Components

The $H\alpha$ - $[N\ II]$ lines were selected for performing the line decomposition over a large area. The $[O\ I]$ and $[S\ II]$ lines

FIG. 4.—Some examples for the fitting of representative spectra

do not have a high enough signal-to-noise ratio (S/N) and therefore cannot be traced farther out without substantially increasing the uncertainties. The line profile decomposition was done such that for the same velocity component the $[\text{N II}] \lambda\lambda 6548, 6583$ intensity ratio was set to a fixed value of 3, and the widths of all lines ($\text{H}\alpha$ and $[\text{N II}] \lambda\lambda 6548, 6583$) were forced to be equal. Also, the lines associated with different gas components were allowed to have different widths, and the $\text{H}\alpha/[\text{N II}]$ intensity ratio was set free in all fits. Finally, the central wavelength of each line was set by calculating the corresponding redshifted vacuum wavelength associated with each velocity component. In some spectra the fits lead to few possible solutions. However, thanks to the fact that our spectra are distributed in two dimensions, we were able to track the kinematic properties of the different components, imposing in some cases additional restrictions to assure regularity on such properties.

Although in some regions evidence for more than two components could exist, we found that a single-Gaussian or a two-Gaussian fit per emission line is able to reproduce most of the observed profiles. Representative examples of the emission-line profiles and their best fits are shown in Figure 4. The $\text{H}\alpha + [\text{N II}]$ emission-line profiles can be classified according to four main categories: (1) profiles typical of the emission lines emitted by the northwest complex, best fitted by two Gaussians, one with a width (FWHM $\sim 18 \text{ \AA}$; e.g., spectra 113 and 125 in Fig. 4); (2) profiles characteristic

of the emission lines emitted by the southeast complex, best fitted by two Gaussians of similar width (FWHM $\sim 7 \text{ \AA}$; e.g., spectra 100 and 81 in Fig. 4); (3) profiles best fitted by a narrow single Gaussian (FWHM $\sim 4.5 \text{ \AA}$) and with H II -like emission-line ratios (e.g., 114 and 68 in Fig. 4); and finally (4) profiles typical of the emission lines emitted by the regions outside the southeast and northwest complexes, best fitted by a single Gaussian (FWHM $\sim 6 \text{ \AA}$) with LINER-like emission-line ratios (e.g., 129 and 70 in Fig. 4).

Taking into account the spatial distribution of the fit parameters, we can identify three distinct kinematic gaseous components, whose velocity fields (and spatial distribution) are presented in Figure 5.

The main component (hereafter component R) is detected nearly everywhere over the entire $14'' \times 12''$ region, and its velocity field is similar to the one obtained by fitting the $[\text{N II}] 6583 \text{ \AA}$ emission-line profile to a single Gaussian (see velocity field in Fig. 3). The width of component R, characterized by an average FWHM of $6 \pm 1.5 \text{ \AA}$, or 270 km s^{-1} , indicates that this gas is not kinematically disturbed by either the merging process or the winds induced by the nuclear starbursts. The velocity pattern, with a peak-to-peak velocity of 450 km s^{-1} , can be interpreted as regular rotation around the obscured nucleus and with the minor kinematic axis oriented along the southeast-northwest direction (P.A. $135^\circ \pm 15^\circ$).

A broad component (hereafter component B) that has an average width (FWHM) of about $18 \pm 6 \text{ \AA}$ (i.e., corresponding to an average velocity range of 815 km s^{-1}) is detected in the northwest complex over an extended region of about 2.5 ($\sim 1 \text{ kpc}$) in diameter. Component B is blueshifted by about 300 km s^{-1} with respect to the systemic velocity.

A third component (hereafter component O) is associated with one of the Gaussians needed to adjust the profiles of the lines emitted by the southeast complex and with the narrower emission line component detected in some spectra in the northwest complex (124, 125, and 126 in Fig. 1). In fact, the kinematic properties of this narrow line in these spectra do not fit with those of components R and B but have a continuity with the blueshifted component O detected toward the southeast complex, providing its redshifted counterpart. The line width of component O (average FWHM of $8 \pm 1.2 \text{ \AA}$, or 360 km s^{-1}) reveals the existence of ionized gas kinematically more disrupted than the rotating gas (component R). Also, the peak-to-peak projected velocities are about 1000 km s^{-1} , and the distribution of this ionized gas is well aligned along the kinematic minor axis of component R. Therefore, the width and peak-

FIG. 5.—Velocity field and spatial distribution of the three main kinematically distinct gaseous components in Arp 220. Note that the three images are presented with the same color scale for better comparison.

to-peak velocity of component O reveal the presence of a highly disrupted gas component undertaking strong radial motions.

Based only on the $[\text{N II}] \lambda 6583/\text{H}\alpha$ ratio, the ionization status of the different gas components identified above is very similar, with no evidence for an ionization gradient either along the axis of the outflowing gas or transverse to it. The three ionized gas components (R, B, and O) have average $\log [\text{N II}]/\text{H}\alpha$ values of $0.46(\pm 0.25)$, $0.48(\pm 0.17)$, and $0.52(\pm 0.22)$, respectively.

3.4. Two-dimensional Velocity Field and the Starburst-driven Galactic Winds Scenario

The schematic picture of starburst-driven galactic superwinds is that the collective effects of supernovae and massive star winds generated in a nuclear starburst are able to compress and sweep the ambient interstellar medium with velocities of a few hundred km s^{-1} in a direction perpendicular to the disk of the galaxy, i.e., along the direction of the maximum pressure gradient (Heckman et al. 1990 and references therein). The three kinematic components of the ionized nebula identified in the inner 2 kpc around the dust-enshrouded nucleus of Arp 220 reveal a velocity pattern that is consistent with the basic scenario of starburst-driven galactic superwinds.

Component R (i.e., rotational) has a rather regular kinematic pattern that, to first order, can be explained by a rotating disk. This component of ionized gas could be coupled with the 1 kpc scale molecular disk detected in CO (Scoville et al. 1997) and with the 100 kpc disklike H I gas that also shows a rotation pattern in the same sense as the molecular disk (Yun & Hibbard 2001). In fact, the ionized gas has the same velocity range and kinematic major axis as the nuclear disk of molecular gas (Scoville et al. 1997), and it also rotates in the same direction as the eastern nucleus embedded in the 1 kpc molecular disk (Sakamoto et al. 1999).

It is interesting to note that the major kinematic axis of all the above-mentioned rotating gas components are not well aligned with the corresponding axis of the large-scale stellar distribution. Optical (Hibbard et al. 2000) and infrared (Scoville et al. 1998) images show that the major axis of the large-scale optical plume is aligned along the northwest direction, offset by about 45° – 60° with respect to the kinematic major axis of the nuclear disk of gas. This is a clear indication that the gas and stars have a different spatial distribution, likely as a consequence of the tidal forces involved in the advanced merging process that is taking place in Arp 220 or as a consequence of gas and stars coming from the different progenitor galaxies involved in the merger.

Following the scenario proposed by Heckman et al. (1990), the kinematic component O, with projected peak-to-peak velocities of $\sim 1000 \text{ km s}^{-1}$, can be interpreted as the gas associated with the edge of the biconical outflow (see Fig. 6, which is similar to the schematic Fig. 19 of Heckman et al. [1990] adapted for the case of Arp 220). The O component represents the gas over the closest edge of the upper cone (southeast) and the farthest edge in the bottom cone (northwest). The symmetry axis of the outflow is oriented along P.A. 135° , i.e., along the minor axis of the rotational disk component, as expected in the standard superwind scenario. The blueshifted broad component B traces gas approaching us and located close to the center of the

FIG. 6.—Adaptation of Fig. 19 of Heckman et al. 1990 for the case of Arp 220. It represents the schematic of outflow along a biconic surface centered on the nucleus. Note that the disk is represented along the minor kinematic axis (southeast-northwest direction). Line of sight of the observer is also indicated for two cases: northwest and southeast directions. According to this scenario, the different kinematic components found in this work (Fig. 5) are identified.

expanding bubble (Fig. 6, closest edge in bottom cone). Because of projection effects and the fact that this gas is moving close to the disk, the widths of the lines associated with this gas are broader. The red counterpart of this component (farthest edge in upper cone) is not seen. This may be due to projection effects (edge of the cone nearly perpendicular to the line of sight) or to an intrinsically faint emission in this zone.

Note that this interpretation imposes some geometrical restrictions. In particular, the inclination (i) should be smaller than 45° and the opening angle for the cones (Θ) larger than $2i$. Provided that CO studies (Scoville et al. 1997) suggest $i \sim 45^\circ$, we propose $i \sim 30^\circ$ and $\Theta \sim 90^\circ$ as a compromise solution also compatible with our kinematic values.

The overall geometry and kinematics of the nuclear regions and galactic superwind in Arp 220 can now be better understood. The molecular gas (Scoville et al. 1997) and the rotating ionized gas trace a nuclear disk of about 1.5 kpc radius and about 30° inclination with respect to the line of sight. The large velocities measured in the rotational ionized gas component R correspond to a dynamical mass (M_{dyn}) of about $2 \times 10^{10} M_\odot$ within a radius of ~ 1.5 kpc. This high value for the dynamical mass indicates a large mass concentration in the nuclear regions of Arp 220, as already inferred by the presence of $5 \times 10^9 M_\odot$ of molecular gas within a radius of 250 pc (Scoville et al. 1997). The bipolar superwind cone is tilted by 90° along the spin axis of the rotating disk and has an opening angle of about 90° , as suggested by the morphology of the region where the high-velocity component O has been detected.

Although from a kinematic point of view the present data support the picture described above, this implies that the northwest complex is seeing through the dusty disk of Arp 220. The relative intensities of the northwest and southeast complexes suggest the opposite. This is an additional indication that the distribution of gas and dust in the inner

regions of Arp 220 are very complex and require more detailed study.

3.5. Two-dimensional Ionization Structure

The two-dimensional ionization structure of the ionized gas in the nuclear regions of Arp 220 shows, on average, a homogeneous radiation field. There are, however, some well-localized regions where a change in the ionization properties, and maybe in the ionization mechanism, is detected.

Based on the $[\text{N II}] \lambda 6583/\text{H}\alpha$ and $[\text{S II}]/\text{H}\alpha$ ratios (note the low S/N of the $[\text{O III}]$ and $\text{H}\beta$ lines), the overall emission is consistent with LINER-like emission. The three identified components (R, B, and O) have average $\log [\text{N II}]/\text{H}\alpha$ values of $0.46(\pm 0.25)$, $0.48(\pm 0.17)$, and $0.52(\pm 0.22)$, respectively. On the other hand, the $\log [\text{S II}]/\text{H}\alpha$ ratio has average values of 0.11 ± 0.10 and 0.15 ± 0.12 for the northwest and southeast ionized regions, respectively. Moreover, there is no evidence, within the uncertainties, of excitation gradients along the symmetry axis of the outflow, nor is there evidence of a biconical ionization structure, which indicates that the ionizing radiation field is not as collimated as the outflowing gas.

Additional line ratios such as $[\text{O III}]/\text{H}\beta$ and $[\text{O I}]/\text{H}\alpha$ have been measured for the high surface brightness northwest complex. The lower limits to the $[\text{O III}]/\text{H}\beta$ ratio ($\log [\text{O III}]/\text{H}\beta \geq 0.7$) and the $[\text{O I}]/\text{H}\alpha$ ratio ($\log [\text{O I}]/\text{H}\alpha \geq 0.13$) are consistent with the classification of the extended ionized gas in this region as a Seyfert 2 nebula.

As mentioned above, there are some well-identified regions where a drop by a factor of 5 in the $[\text{N II}] \lambda 6583/\text{H}\alpha$ ratio is measured with respect to the general ionization field. These regions are widely separated and are distributed mostly in the western side of the galaxy in (1) a zone at about ($5''.5, 1''.5$) (spectra 51, 52, and 68 in Fig. 1) that seems to be associated with a faint source visible in the WFPC2 *I*-band image; (2) a zone at about ($-0''.5, -0''.5$) (spectrum 114 and surroundings), which could be coincident with the knot detected in the *I*-band image at ($-0''.3, -0''.4$); (3) a zone at about ($7''.5, -2''.5$) (spectra 19 and 20); and (4) a zone at about ($-3''.5, 2''.0$) (spectrum 78 and neighbors), where one of the emission-line components has a $\text{H}\alpha/[\text{N II}]$ value above 1. The average $\log [\text{N II}]/\text{H}\alpha$ ratio of all these regions is -0.2 ± 0.1 , which is close to that of H II regions. However, none of these regions coincide with the star clusters found in the infrared by Scoville et al. (1998). Additional emission-line ratios are needed to firmly support the idea that the ionization of these regions is due to hot stars rather than to wind-generated shocks.

4. SUMMARY

Two-dimensional integral field optical spectroscopy with the INTEGRAL system has been used to investigate the dust-enshrouded nucleus of Arp 220 and its surrounding circumnuclear regions within 2 kpc from the nucleus. A complete two-dimensional description of the complex distribution, kinematics, and ionization status of the warm ionized gas has been established.

The distribution of the stellar and warm ionized gas has been studied using the optical continuum and line imaging, centered on various optical emission lines. The main results are as follows:

1. Because of the large internal extinction toward the nuclei, the brightest stellar and line-emitting regions at

optical wavelengths do not coincide with the dust-enshrouded near-infrared and radio nuclei of Arp 220 but rather are located northwest of the nucleus, at a distance of about 750 pc.

2. The stellar and ionized gas share similar distributions. However, the ionized gas is more concentrated toward the northwest, and its emission peak is located about 300 pc southwest from the optical stellar emission peak.

Different kinematic gas components have been identified and their two-dimensional velocity fields have been established by means of a two-dimensional multiple-component line analysis. The main results regarding the kinematics of the ionized gas are as follows:

3. Three main kinematic components have been identified in the ionized gas. One of these components (R) is well interpreted as rotation, while the other two (O and B) are associated with a biconical outflow. The two-dimensional kinematic structure supports the starburst-driven galactic winds scenario proposed by Heckman et al. (1990).

4. The rotational gas component R is consistent with quiescent gas in a disk with the spin axis along the southeast-northwest direction (P.A. 135°). The rotational velocities imply a dynamical mass (M_{dyn}) of $2 \times 10^{10} M_\odot$ within a radius of 1.5 kpc. This high value for the dynamical mass indicates a large mass concentration in the nuclear region of Arp 220, as already inferred by the presence of $5 \times 10^9 M_\odot$ of molecular gas in a nuclear 0.5 kpc size gas disk (Scoville et al. 1997).

5. Two gas components are associated with the closest and farthest edges of the biconical outflow. One of these gas components (O) shows peak-to-peak velocities of 1000 km s^{-1} . The other (B) is a broad component (815 km s^{-1} FWHM) located at about 600 pc northwest of the dust-enshrouded nucleus and blueshifted by 300 km s^{-1} with respect to the systemic velocity. This gas component represents gas near the center of the expanding bubble where, because of projection effects and its proximity to the disk, the lines are broader.

The two-dimensional structure of the radiation field has been traced by the maps of the different emission lines and their corresponding ratios. The main conclusions regarding the ionization status of the gas and the nature of the ionization sources are as follows:

6. In spite of the biconical kinematic structure, there are no traces of large ionization gradients or of a biconical ionization structure associated with the outflowing gas. This indicates that the ionizing radiation field is more homogeneous and not as collimated as the outflow.

7. The overall optical spectral properties of the ionized gas inferred from the $[\text{N II}] \lambda 6583/\text{H}\alpha$ and $[\text{S II}]/\text{H}\alpha$ ratios are consistent with LINER-like emission. However, the lower limit of $\log [\text{O III}]/\text{H}\alpha > 0.7$ in the northwest complex is typical of Seyfert 2 nebulae.

8. None of the circumnuclear clusters detected previously in the near-infrared by Scoville et al. (1998) show indications of H II-like excitation, supporting previous results that suggest that they are old clusters. Four independent extranuclear regions are identified where the $[\text{N II}]/\text{H}\alpha$ ratio is close to the typical value of H II regions. Additional line ratios are needed before any firm conclusion about the nature of the ionization source of these regions is reached.

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