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COMPLEX STRUCTURE OF SUPERWIND-DRIVEN NEBULA AROUND THE ULTRALUMINOUS INFRARED GALAXY ARP 220 [a]

[a]BASED IN PART ON DATA COLLECTED AT SUBARU TELESCOPE, WHICH IS OPERATED BY THE NATIONAL ASTRONOMICAL SOCIETY OF JAPAN.

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ABSTRACT

We present results of new optical narrow-band imaging and long-slit spectroscopy of a superwind-driven nebula around an archetypical ultraluminous infrared galaxy, Arp 220. Although the nebula is known to show a simple "figure-8" shaped morphology and is often recognized as a pair of twin bubbles, we find that the nebula has rather complex properties than expected from its simple appearance. In Hα and [N II]$\lambda\lambda$6548, 6583 image, we identify two more pairs of smaller shell-like morphological features within the twin bubbles previously known. By analyzing the kinematical structure along the major axis of the nebula, we find that the inner region between 6$''$ SE and 2$''$ NW shows a broad emission-line component whose full width at half maximum (FWHM) varies from $\sim$ 500 km s^{-1} to 1200 km s^{-1} as well as the narrow one with FWHM $\simeq$ 250 km s^{-1}. On one hand, a double-peaked narrow profile is found at $6-9''$ SE, $\sim 12''$ SE, and 11$''$ NW and a single narrow blue-shifted profile is found in the remaining parts. These complex morphological and kinematical properties are difficult to be interpreted simply as the effect of the expanding twin bubbles. Rather, a model of overlapping multiple bubbles each of which has different size and kinematical structure seems to be more preferred since each shell-like structure seems to have its own kinematical characteristics. It is therefore suggested that Arp 220 experienced multiple starburst events in its central region.

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

1. INTRODUCTION

Since their discovery in 1984 (Soifer et al. 1984), much attention has been paid to the ultraluminous infrared galaxies (ULIGs) population because their bolometric luminosities are $\sim$ 100 times as high as those of typical disk galaxies, and almost entirely emitted in the infrared (e.g., Soifer et al. 1987; Sanders & Mirabel 1996). The infrared radiation is believed to come from dust grains heated by nearby energetic sources. A still hotly debated question is: what powers ULIGs, and why ULIGs are so luminous? There are two alternative energy sources. One is active galactic nuclei (AGNs) like quasars which are thought to be powered by gas accretion onto a supermassive black hole (e.g., Rees 1984). The other is a super-starburst: a large number of massive stars formed in a burst mode (e.g., Emerson et al. 1984). Recent mid-infrared and hard X-ray observations suggest that the dominant energy source in the majority of ULIGs is a super-starburst rather than a hidden AGN (Genzel et al. 1998; Lutz, Veilleux, & Genzel 1999; Iwasawa 1999). In such starburst-dominated ULIGs, the rate of energy input into the surrounding interstellar medium by hot stars, stellar winds, and supernova explosions are expected to be large enough to drive energetic outflows of ionized gas, or "superwinds" (e.g., Chevalier & Clegg 1985). Indeed, many ULIGs show evidence of such outflows [Heckman, Armus, & Miley 1990 (hereafter, HAM90); Lehnert & Heckman 1996]. Therefore, it is important to investigate how such superwinds affect the observational properties of ULIGs (HAM90; Heckman et al. 1996, 2000; Taniguchi & Ohyama 1998; Taniguchi et al.

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1999).

Arp 220 (Arp 1966) is the nearest and best-studied ULIG (e.g., Sanders & Mirabel 1996). It has two starburst nuclei in its center (e.g., Condon et al. 1991; Taniguchi & Shioya 1998 and references therein) and an infrared luminosity between 8 μm and 1000 μm of $1.5 \times 10^{12} L_{\odot}$. It also shows unambiguous evidence for superwind activity which is manifested both by the emission-line morphology (i.e., the figure-8 shaped emission-line nebula extending to a radius of 15 kpc) and the kinematical property expected for the expanding bubble [Heckman, Armus, & Miley 1987 (hereafter, HAM87); HAM90; Heckman et al. 1996]. The ionization of this gaseous nebula is dominated by shock heating rather than photoionization by massive stars (HAM87; Taniguchi & Ohyama 1998; Taniguchi et al. 1999). In the central region of Arp 220, there are a number of luminous star-forming regions (Shaya et al. 1994; Scoville, Yun, & Bryant 1997). However, their number and energy output are insufficient to explain the huge bolometric luminosity of Arp 220 and thus the majority of the starburst is thought to be buried by massive amounts of gas and dust (Genzel et al. 1998; Shioya, Taniguchi, & Trentham 2001; Shioya, Trentham, & Taniguchi 2001). Therefore, it is intriguing to investigate the central region of Arp 220 in more detail. Motivated by this, we have obtained optical spectroscopy on the Keck II 10 m telescope and optical imaging on the Subaru 8 m telescope at Mauna Kea Observatories of Arp 220. We use a distance of 74 Mpc. This distance is estimated by using the recession velocity to the Galactic Standard of Rest, $V_{\rm GSR} = 5531$ km s^{-1} (de Vaucouleurs et al. 1991) and a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}. At this distance, $1''$ corresponds to 360 pc.

2. OBSERVATIONS AND RESULTS

2.1. *Narrow-Band Imaging*

In Figure 1 we show the morphology of the starlight and ionized gas in Arp 220. These images were obtained on UT 2000 March 15 during the commissioning run of the FOCAS (Faint Object Camera And Spectrograph; Kashikawa et al. 2000) attached at the Cassegrain focus of the Subaru telescope (Kaifu 1998). Exposure time was 1200 seconds in each integration. Figure 1a presents a narrow-band optical image centered at λ6588Å with a bandwidth of 73Å. This image probes the stellar continuum emission, which is affected by obscuring dust in the interstellar medium of Arp 220. In Figure 1b, we show a continuum-subtracted Hα+[N II]$\lambda\lambda$6548,6584 emission-line image, made by subtracting the image at λ6588Å from a narrow-band image taken at λ6709Å with a bandwidth of 85Å which covers the redshifted Hα and [N II] emission. A contrast-enhanced emission-line image is shown in Figure 1c. Clearly, the ionized gas morphology is quite different from the continuum morphology. Finally, Figure 1d shows a schematic representation of various ionized gas features discussed below.

The most remarkable property of the ionized gas is the presence of several shell-like structures. The largest pair of shells extends up to $\simeq 40''$ into both SE and NW directions. This figure-8 shaped structure was previously described by HAM87 and HAM90, who called it a "double-bubble". We refer to this feature as superbubble A, with the two lobes labeled $\rm A_{SE}$ and $\rm A_{NW}$ for each bubble extending SE and NW direction, respectively, in Figure 1d. This structure is thought to be made by a large number of supernovae associated with a starburst $\sim 3 \times 10^7$ years ago (Armus et al. 1995; Heckman et al. 1996). In addition to this large-scale pair of superbubbles, there appear some smaller-scale shells at smaller radii. Although the structure is rather complex, we tentatively identify two pairs of shells ($\rm B_{SE}$ and $\rm B_{NW}$, and $\rm C_{SE}$ and $\rm C_{NW}$) and are labeled in Figure 1d. The most remarkable shell is a $\rm C_{SE}$ which is recognized as a bright curved ridge extending SE of the nucleus. Around $\rm C_{SE}$ there seems to be a fainter shell of similar appearance, $\rm B_{SE}$, extending up to $r \simeq 10''$ from the nucleus, which is visible more clearly as faint fuzz surrounding $\rm C_{SE}$ in Figure 1c. Although this shell is faint, we attribute it to another shell because we find that two bright emission-line knots are likely to be associated with this shell. We also note that $\rm B_{SE}$ has a clear counterpart of similar size, $\rm B_{NW}$, which is an inner loop structure within $\rm A_{NW}$. Since there is no optical continuum counterpart to either knot on $\rm B_{SE}$, their origin is unknown. The last shell, $\rm C_{NW}$, is a small round bubble or a compact cluster of knots at just NW of the dust lane around the nucleus ($-3'' \lesssim r \lesssim 2''$). In the close up image shown in Figure 2a, there seem to be a few spatially resolved emission-line knots along the shell. Although we identify this region as a counterpart of $\rm C_{SE}$ simply because $\rm C_{NW}$ and $\rm C_{SE}$ are the smallest features at both sides of the nucleus, this might belong to just another smaller shell. Note that these identifications are tentative ones, and it is not clear whether pairs of bubbles ($\rm B_{SE}$ and $\rm B_{NW}$, and $\rm C_{SE}$ and $\rm C_{NW}$) are indeed physically related ones. Although some of the structures described above were detected in the emission-line image obtained by HAM87 (see also Heckman et al. 1996), no clear description of each feature was given. We also identify a pair of curved features or "spurs" directed to the north and south which may be a pair of broken superbubbles (De Young & Heckman 1994). The southern spur seems to be physically related to the so-called southern extension found in radio continuum images (e.g., Condon et al. 1991). The observational properties of the three shell-like structures and spurs are summarized in Table 1.

2.2. *Spectroscopy*

In Figure 2 we show our optical spectrum of the inner $40''$ region of Arp 220. The spectrum was taken with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck II Telescope on the night of UT 1997 April 16. A 900 s exposure was taken with the 600 line mm^{-1} grating, with a central wavelength setting of 6024 A. The grating is blazed at 5000Å and the dispersion is 1.28 A pixel^{-1}. The observational setup yielded wavelength ranges and resolutions of 4670Å - 7210Å and 6.9Å, respectively. The $1''$ slit was oriented at the position angle (PA) of 130 deg to observe both the nucleus and its visual companion D ($\sim 2'$ SE of Arp 220) simultaneously (Ohyama et al. 1999). This position angle is almost similar to that of the bright inner nebula within nuclear $\pm 10''$ region (Heckman et al. 1996). More detailed information on the observing conditions can be found in Ohyama et al. (1999). By comparing the spatial distribution of Hα + [N II] flux in the spectrum and that in the continuum-subtracted emission-line image calculated at various possible slit positions with PA=130 deg, we aligned the slit position on the image. We found that the slit was actually placed on the northern part of C_{NW} which corresponds to the brightest part of the spectrum at $r \simeq -1''$– $-2''$ and on a northern ridge of C_{SE} which corresponds to the second brightest part of the spectrum at $r \simeq 3''$– $8''$. The slit registration accuracy would be less than $\pm 0.5''$ because we could not explain both peaky flux distribution around C_{NW} and almost flat one around C_{SE} at the same time if the slit was placed more NE or SW positions. After removing the stellar continuum spectrum, the emission-line spectrum around Hα and [N II] is shown along with the emission-line image in Figures 2a and 2b, respectively. Note that the narrow-band image in Figure 2a is the inner $17'' \times 40''$ portion of Figure 1b, but is rotated by 50 deg clockwise so that the slit position is shown horizontally (shown by two horizontal lines in Figure 2a). These images are useful in comparing the morphology and kinematical structures of the ionized gas around the nuclear regions.

To show the complex velocity structure quantitatively, we performed the Gaussian fitting to the line profiles. We first tried to fit the profiles with two sets of Hα+[N II] components, and then fit them with a single set of the lines for the region where the two-set fit results suggest the presence of only a single set of the lines. The profiles can be represented very well either by the narrow [full width at half maximum (FWHM) $\simeq$ 250 km s^{-1}] plus broad (FWHM $\sim$ 500 – 1200 km s^{-1}) Gaussian components [an example is shown in Figure 2c(II)], or by two narrow (FWHM $\simeq$ 250 km s^{-1}) Gaussian components at different velocities [examples are shown in Figure 2c(I) and (III)], or by a single narrow (FWHM $\simeq$ 250 km s^{-1}) Gaussian component. The fitting results are shown in Figures 2d, 2e, 2f for radial velocity, FWHM, and spatial variation of the [N II]λ6584/Hα ratio, respectively. We can identify three regions with narrow double-peaked profiles (see Figure 2c and 2d). The first two appear along the SE ridges of shells C ($r \simeq 6'' - 9''$) and B ($r \simeq 12''$), and the other is along the NW ridge of the shell B ($r \simeq -11''$). The velocity-splitting at the location of the latter feature was discovered and described by HAM90. The velocity difference between the double peaks are $\Delta V_{\rm r} \simeq$ 300, 430, and 300 km s^{-1} for SE ridge of shell C, SE ridge of shell B, and NW ridge of shell B, respectively. Such double-peaked profiles are typical of nearby superwind galaxies with expanding biconical ionized gas, with the different kinematic components arising from gas on either the near or the far sides of the cone (e.g., HAM90; Lehnert & Heckman 1996). Some parts of B_{SE} ($r = 2''$– $10''$) and the inner region of A_{SE} and A_{NW} ($r = 13''$– $15''$, and $-12''$– $-20''$) show only the emission-line component which is blue-shifted by $\simeq$ 300 km s^{-1} with respect to the systemic velocity[2]. Such blue-shifted components are also found for the broad component around the nuclear region within C_{SE} and C_{NW}. These components could be a blue-shifted one of the double-peaked profile whose red-shifted counterparts are hidden by dust grains.

Although the Hα emission may be suppressed because of the underlying stellar Balmer absorption (e.g., Armus et al. 1995), the observed high [N II]λ6584/Hα ratios (exceeding 2 over the observed region; Figure 2f), which is a useful indicator of the excitation mechanism of the ionized gas, suggest that the major ionization source for all the features found in the spectrum is shock heating rather than photoionization by massive stars (HAM87; HAM90; Taniguchi et al. 1999).

3. DISCUSSION

We have found that the 8-figure shaped twin bubbles (bubble A) (HAM90; see also HAM87) show rather complex structures in its inner region. We identify two smaller shells, B and C, inside bubble A, and a possible pair of spurs in the narrow-band image. One might think that these identifications are based just on an examination of the ionized gas morphology, and each component which we claim as an individual 'shell' might indeed be a part of a single larger bubble A modified apparently by dust extinction. However, we find that shells identified on the narrow-band image can also be recognized in the velocity structure on the spectrum, suggesting strongly that they are indeed individual shells having their particular kinematical structures. Here we describe how the change of the kinematical properties and that of the morphology of the ionized gas are closely related to each other. Remarkable broad component is detected only in both C_{NW} and inner part of C_{SE}. B_{SE} corresponds spatially to the region where double-peaked profile is detected, and is located at just outside the SE tip of the curved C_{SE} ridge ($r \simeq 10''$). Both inner and outer regions from B_{SE} show a single profile, and they can be attributed to other shells (C_{SE} and A_{SE} for inner and outer regions, respectively). At NW of the nucleus, single blue-shifted component is detected up to $r = -10''$, and it suddenly changed to the double-peaked profile at the boundary between B_{NW} and A_{NW}. A_{NW} can be recognized as a region showing relatively constant velocity field beyond B_{NW}. Although the spectrum corresponding spatially to A_{SE} is faint, it seems likely that this region also shows a single-peaked component, like A_{NW}. Given such a close correlation between the morphology and the kinematical structures, it seems natural to consider that each shell has its own kinematical structure and we see several shells overlapping in the inner nebula of Arp 220, leading a complex structure of its nebula.

Here a question arises as what the origin of the smaller shell-like structures is. One possible idea is that they are created as an expanding superbubble A interacts with the inhomogeneous ambient matter. In typical superwind galaxies, the expanding ionized-gas bubble interacts with the circumnuclear dense-gas disk at first, and is collimated toward the minor axis of the galaxy to form either a pair of elongated bubbles (without breakout) or bi-directional cones (with breakout) (e.g., Tomisaka & Ikeuchi 1988; HAM 90; Suchkov et al. 1994). In this case, the bubbles would show relatively simple shapes because the bubbles expand in sweeping out the tenuous halo gas. In the case of Arp 220, however, it seems very likely that the past violent galaxy-galaxy merging has brought some part of the dense gas around the nucleus to off-nuclear regions, forming in-

[2]The systemic velocity is estimated as $\simeq$ 5500 km s^{-1} by using the most red-shifted emission-line velocity around the nuclear region (Figure 2d), which is consistent with the value estimated by CO(2 – 1) emission (Scoville et al. 1997; Sakamoto et al. 1999).

homogeneous ambient gas distribution around the galaxy. In fact, HI observation clearly shows the presence of such matters (Hibbard et al. 2000). The shell-like structures would be formed where the expanding hot gas interacts with the blob of ambient matter to form local shock fronts. Note, however, that the superbubble would still form a bi-directional bubble-like structure in larger scale because it is likely to be collimated initially by the compact circum-nuclear dense gas disks (Scoville et al. 1997; Sakamoto et al. 1999). One difficulty of this model is that the largest bubble A shows the simplest and smoothest structure among the bubbles or shells, which is inconsistent with the model because the larger bubbles would show more disturbed morphology as it develops to larger distance from the nucleus through inhomogeneous matter.

Another alternative idea is that there are several individual bubbles of different sizes and kinematical structures and, hence, the different origins. In this model, each bubble should originate from each starburst event occurred at different epoch since the expected ages of the bubbles differ significantly from each other. We estimate the age of each superbubble ($t_{\rm sb}$) following Heckman et al. (1996), which applies the superwind model of Chevalier & Clegg (1985). The radius of the superbubble (i.e., shocked shells) at time $t_{\rm sb,7}$ (in units of 10^7 yr) is parameterized as:

$$r_{\rm shell} \sim 7 L_{\rm mech,43}^{1/5} n_{\rm H,-2}^{-1/5} t_{\rm sb,7}^{3/5} \ \ {\rm kpc}, \tag{1}$$

where $L_{\rm mech,43}$ is the mechanical luminosity released collectively from the supernovae in each starburst in units of 10^{43} ergs s^{-1} and $n_{\rm H,-2}$ is the average hydrogen number density of the interstellar medium, assumed constant in units of 10^{-2} cm^{-3}. This equation can be inverted to solve for the age of the different shells. Using the maximum radius of each shell, we obtain $t_{\rm sb,7} = 3.2$, 1.0, and 0.23 for bubbles A, B, and C, respectively (see Table 1). We can also estimate the dynamical timescale of each superbubble using the relation $t_{\rm dyn} = r_{\rm max}/v_{\rm exp}$, where $v_{\rm exp}$ is the expansion velocity of the bubble (HAM90). The results are given in Table 1. We find that the two timescales differ by factors of 1.5, 3.2, and 2.3 for bubbles A, B, and C, respectively; but it can be said that they are consistent within a factor of three. If we consider the possibility that the pair of spurs is the remnants of a previous wind-blown superbubble, we may conclude that Arp 220 experienced at least three or perhaps four separate starbursts, giving rise to the separate superbubbles identified in this study. If this is the case, one may expect that the velocity structure around the near-nuclear region should be very complex because both the blue- and red-shifted components of all bubbles should be seen in overlapping regions around the nucleus. On the contrary, our data show only the blue-shifted component in some regions within shells B and C ($r = -10''$–$-2''$, and $10''$– $11''$). This may be because the emission-line flux of larger bubbles are relatively weak comparing with that of the bright inner bubbles, and the red-shifted component coming from the far side of the inner bubbles might be extinct by dust grains which are widely distributed out to ~ 3 kpc from the nucleus by tidal effect of the galaxy merging.

Both models for complex bubble structures around Arp 220 seem to be promising and we cannot discriminate the two possibilities solely using our data. However, we prefer the model of multiple bubbles since it has no major difficulties if we assume the multiple starburst events in this galaxy. Here we note that the orbital period of double nuclei in Arp 220 is $t_{\rm orbit} \sim 3.5 \times 10^7 M_9^{-1/2} l_{500}^{3/2}$ yr where M_9 is the total dynamical mass of the double nuclei in units of $10^9 L_\odot$ (Larkin et al. 1995; Scoville et al. 1997) and l_{500} is the separation between the two nuclei in units of 500 pc. If we consider the possibility that the starburst event is triggered by dynamical disturbance when the two nuclei are closest to each other, one may expect periodical starburst events every several times 10^7 yr (e.g., Taniguchi & Wada 1996). We point out that this period is nearly the same as the spread of ages among the bubbles. Our study suggests that the detailed analyses of the superbubble structures can be used to understand the past starburst activities of the host galaxy and, hence, to understand the formation and evolution of this merging galaxy. If the multiple nature of the super-starburst activities of Arp 220 is true, it would pose a significant impact in understanding what is going on in this prototypical ULIG.

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FIG. 1.— The continuum image at λ6588Å and the continuum-subtracted, red-shifted emission-line (Hα and [N II]$\lambda\lambda$ 6548,6584) image of Arp 220 are shown in panels (a) and (b), respectively. Panel (c) is a contrast-enhanced image of panel (b) and shows faint emission-line feature. For readers' convenience, contours are also shown. A bad CCD column is masked in panels (a), (b), and (c). A schematic illustration of the identified shells (see also Table 1) is shown in panel (d).

FIG. 2.— The optical spectrum of the nuclear 40″ region [panel (b)] is shown along with the inner part of the nebula [panel (a)] taken from panel (b) of Figure 1. An image in panel (a) is rotated by 50 deg clockwise. Note that the continuum emission is subtracted in panel (b) for direct comparison with panel (a). In panel (c), we show observed emission-line profiles (histograms) and the model Gaussian profiles (lines) of the three regions marked in panel (b). Spatial variations of the radial velocity (V_r), the line width (FWHM), and the [N II]λ6584/Hα ratio are shown in panels (d), (e), and (f), respectively. The data for the broad components are shown in blue in panels (c), (d), (e), and (f).

ID	$r_{\rm max}$ (kpc)	PA (degree)	$v_{\rm exp}$ (km s^{-1})	$t_{\rm sb}$ (yr)	$t_{\rm dyn}$ (yr)
Bubble A	14	115	300	3.2×10^7	4.7×10^7
Bubble B	7.2	125	220	1.0×10^7	3.2×10^7
Bubble C	2.9	135	530	2.3×10^6	5.4×10^6
Spur	~ 5	~ 0	$\cdots$	$\cdots$	$\cdots$

Table 1

A summary of the multiple shells. The position angle (PA) is measured counterclockwisely from the north. The radius ($r_{\rm max}$) is the maximum radius of each bubble projected on the sky. The expansion velocity ($v_{\rm exp}$) is the maximum velocity difference within each bubble between the blue-shifted emission-line peak and the systemic one for bubbles A and C while a half or the velocity difference between the double emission-line peaks for bubble B.