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THE DOUBLE NUCLEUS OF ARP 220 UNVEILED

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ABSTRACT

Infrared imaging at the f/415 focus of the Palomar 200 inch (5 m) telescope with 0"39 × 0"49 resolution is used to show that the ultraluminous *IRAS* galaxy Arp 220 has a double nucleus with separation 0"95. This high resolution was achieved by taking a series of 5 s exposures, centroiding, shifting to a common origin, and then co-adding. The presence of two closely separated nuclei (330 pc) in Arp 220 confirms the circumstantial evidence—disturbed optical morphology, remnants of tidal tails, and nonconcentric infrared isophotes—that it is an evolved merger remnant. Both nuclei are clearly resolved showing barlike morphology. The extent of the 2.2 μm radiation is evidence that the flux is most probably dominated by starlight. A remarkable degree of correlation is noted between the infrared and centimeter wavelength radio emission and is used to show that Arp 220 is an ongoing merger containing two active nuclei accompanied by circumnuclear starbursts of moderate intensity. If the nuclear activity is powered by accretion onto black holes, then a black hole binary will be formed. Such a binary may be an essential ingredient of many quasars, and therefore Arp 220 may suggest another connection between mergers, ultraluminous *IRAS* galaxies, and quasars.

Subject headings: galaxies: individual (Arp 220) — galaxies: nuclei — infrared: sources

I. INTRODUCTION

Arp 220, with a far-infrared (8–1000 μm) luminosity of $1.5 \times 10^{12}\ L_\odot$, is the nearest example of the ultraluminous ($L > 10^{12}\ L_\odot$) infrared galaxies discovered in the *IRAS* survey. It is of crucial importance to understand the origin, nature, and ultimate fate of the activity in the ultraluminous infrared galaxies because they are an important constituent of the local universe ($z \lesssim 0.1$), outnumbering Seyfert galaxies or quasars of this luminosity (Soifer *et al.* 1986). A study of the ultraluminous *IRAS* galaxy sample (Sanders *et al.* 1988) shows that all 10 have disturbed morphology, which is strong circumstantial evidence that they are advanced mergers of two spiral disks. Most have optical line ratios characteristic of active nuclei, and all appear to be extremely rich in molecular gas. Sanders *et al.* (1988) have suggested that these galaxies are the initial dust enshrouded stage of a quasar. Consideration of the energy distribution, the space density, and the distorted morphology of nearby quasars suggests that most may have their origin in such systems.

At optical wavelengths Arp 220 shows a bilobal structure which is due to a dust lane which bisects the galaxy. Neither of the optical maxima are associated with galaxy nuclei (e.g., Joy *et al.* 1986). However, there is strong evidence that Arp 220 is the result of a merger of two spiral galaxies because optical images show the remnants of two large, faint, crossed tidal tails (Joseph and Wright 1985; Sanders *et al.* 1988). Further evidence for a recent strong interaction includes the chaotic optical morphology, a large velocity dispersion (600 km s^{-1}) in molecular and H I gas (Mirabel 1982; Young *et al.* 1984; Norris *et al.* 1985), nonconcentric nuclear infrared isophotes (Carico *et al.* 1990), and an outer infrared light profile which follows an $r^{1/4}$ law (Wright *et al.* 1990). Infrared studies, which are much less affected by extinction, reveal a single central 2 μm source embedded in the dust lane (Norris 1985) which has a size < 1" in the north-south direction (Neugebauer *et al.* 1987) but is distinctly elongated by 2" east-west (Carico *et al.* 1990). We have obtained new 2.2 μm images of Arp 220 with the objective of studying the structure of the central regions at high angular resolution.

II. OBSERVATIONS

Arp 220 (IC 4553 = IRAS 15327 + 2340) was observed at the f/415 Gregorian focus of the Hale 200 inch telescope on the night of 1989 August 17 with an infrared camera equipped with a Santa Barbara Research Corporation 58 × 62 InSb direct readout detector array. The pixels correspond to 0"052 on the sky, and the field of view was 3" × 3". All observations were made with a standard 2.2 μm (K) photometric band filter. The weather was clear, and the optical (6000 Å) seeing was estimated to be about 1".

The observations consist of three consecutive 5 s integrations of Arp 220 interspersed with similar observations of a nearby star ($\Delta\alpha = 93''$, $\Delta\delta = 140''$) of comparable brightness. Arp 220 was observed in this fashion 10 times, and the star 7 times. Data reduction consisted of subtracting the thermal emission from the sky and the telescope using median-filtered exposures on blank sky, and the pixel-to-pixel gain variations of the system were corrected for by using a twilight sky frame from which the telescope emission was subtracted.

Star images reveal that the image quality declined significantly after the fifth set of Arp 220 integrations, and therefore only the first five sets were used. The change of the star centroid from frame to frame reveals image motion with $\langle \delta r^2 \rangle^{1/2} \approx 0''1$ on time scales of 15 s. Larger drifts on longer time scales are also present. Offsets were calculated from the star centroids, measured in an 8 pixel (0"42) diameter beam, and the data were combined into a single image after shifting each frame accordingly. The star in the resultant image is reasonably well approximated by an elliptical Gaussian with a full width at half-maximum (FWHM) of 0"39 × 0"49 with the major axis at a position angle (PA) of 50° east from north (Fig. 1). The angular resolution of the current data is thus limited by

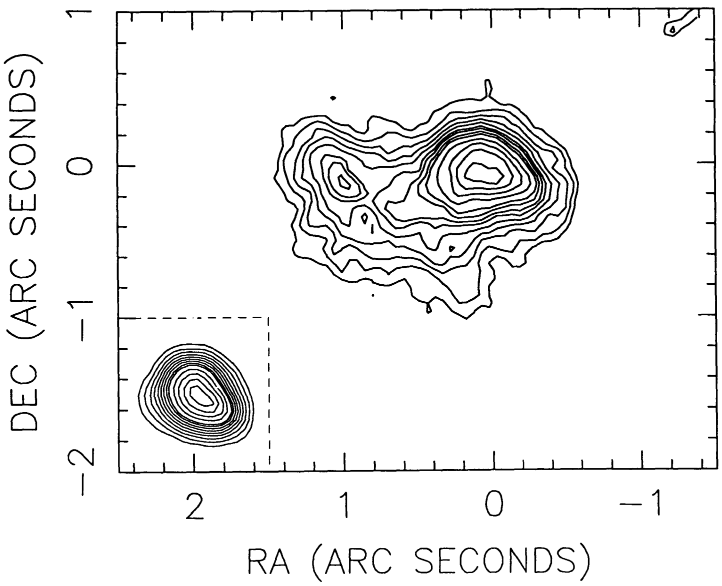

FIG. 1.—The infrared image of Arp 220 at a wavelength of 2.2 μm. The image is comprised of 15 5s exposures which were centroided, shifted to a common origin, and then co-added. The contours are at 0.15–0.55 of the peak in steps of 0.05 and then from 0.65 to 0.95 of the peak in steps of 0.1. The lowest contour plotted corresponds to 4 σ above the sky level. A star which was observed alternately with Arp 220 is shown inset, demonstrating that the beam has a full width at half-maximum of 0″.39 × 0″.49 at a PA of 50°. The same contour intervals were used for the star.

astigmatism of the 200 inch primary mirror and not seeing.[1] Nonetheless, this shift-and-add technique, which removes the first-order seeing–induced blurring due to image motion, leads to a substantial improvement in resolution over direct imaging. Individual 5 s Arp 220 frames show a bright peak with an arc of fainter emission extending approximately 1″ to the east. The centroid of the peak was measured and the frames were shifted to a common origin and co-added to yield the image shown in Figure 1.

III. RESULTS

The 2.2 μm image of Arp 220 shows two resolved sources separated by 0″.95 ± 0″.01 at a PA of 92°. At a distance of 73 Mpc (H_0 = 75 km s^{-1} Mpc^{-1}), 1″ corresponds to 350 pc. Both components are resolved. The brighter western source, which we will denote as Arp 220A, is clearly elongated in an EW direction with a deconvolved FWHM of 0″.75 ± 0″.02 and is also resolved NS with an intrinsic width of 0″.42 ± 0″.01. Figure 1 shows that the eastern source, Arp 220B, is more extended than Arp 220A with a width of 0″.80 ± 0″.02 along a PA of 35°. Perpendicular to this direction the FWHM is 0″.48 ± 0″.02. Thus both nuclei are barlike with aspect ratios of ≈1.7. Neither component shows an unresolved core. The errors on the widths quoted above are purely statistical. Systematic errors in the deconvolved widths can arise if the seeing changes between observations of Arp 220 and the comparison star. These systematic errors are minimized by our strategy of alternating object and reference star observations. To determine the residual systematic error, due to seeing variations which occurred faster than we switched between Arp 220 and the comparison star, we constructed a star mosaic from the first integration of each star observation set, another from the second integration, and a third star mosaic from the third integration. If the seeing was constant, the deconvolved widths of these three star images should be zero, within the statistical uncertainty. However, there is a rms deviation from zero of 0″.06. We assume that the deviation from zero is due to differences between the seeing for the different star observations and use it as a measure of the systematic error in the widths of the components of Arp 220 due to this effect. This systematic error is greater than the statistical errors, but it is substantially smaller than the deconvolved widths, and therefore they are well determined.

The brightness ratio of the sources A and B at 2.2 μm is 1.6, as measured in a 0″.8 diameter beam centered on each nucleus. No photometric standards were measured on that night, but we have used the previously measured camera efficiency to estimate that K(A) = 13.2 mag, and K(B) = 13.7 mag, with uncertainties of 0.2 mag. Figure 1 reveals additional interesting morphology. A filament of emission extends from Arp 220A in a south easterly direction for 0″.5 and then turns towards but does not connect with, B. A low surface brightness lobe is detected extending southward from A for up to 1″. The lowest contour plotted in Figure 1 corresponds to 4 σ above the sky level, and therefore we have high confidence in the reality of these features.

The 2.2 μm position of Arp 220A, as determined by offsetting the telescope from nearby SAO stars, is $\alpha = 15^h32^m46^s.87$, $\delta = +23°40'7''.3$, equinox 1950.0, with uncertainties estimated from internal consistency to be ≈0″.6. The 2.2 μm position of Arp 220A coincides, within the errors, with the western component of the double radio source seen at centimeter wavelengths (Becklin and Wynn-Williams 1987; Norris 1988). It would be desirable to establish the infrared position to higher accuracy to investigate if the radio and infrared emission is coincident on scales smaller than their sizes. However, even in the absence of better infrared coordinates we argue that the high degree of morphological similarity between these wavelengths (see § IV) demonstrates beyond reasonable doubt that infrared and radio sources are very closely associated.

IV. DISCUSSION

The discovery of two closely separated nuclei at K, together with the previous circumstantial evidence, including disturbed optical morphology, remnants of tidal tails, and nonconcentric infrared isophotes, demonstrates that Arp 220 is the product of the merging of two galaxies, an event which undoubtedly triggered the ultraluminous phase now being witnessed. A comparison of the 2.2 μm image shown in Figure 1 with Very Large Array (VLA) data (Becklin and Wynn-Williams 1987; Norris 1988) reveals a remarkable degree of correspondence between the infrared and radio morphology which clarifies the nature of the emission. The radio emission at 6 cm, 2 cm, and 1.3 cm reveals a compact, nonthermal, double radio source with separation 0″.93 at a position angle of 102°. The western radio source, which is coincident with Arp 220A, is brighter than the eastern component. The separation of the infrared and radio nuclei is identical, but because of uncertainty in the orientation of the array, the difference of 10° in the PA is not significant, and we consider that there is little doubt that Arp 220A and B are physically associated with the western and eastern radio sources, respectively. The identification of the compact radio peaks with the infrared nuclei of Arp 220 establishes their

[1] These data were obtained at the beginning of the night before the primary was in temperature equilibrium with the dome air. Astigmatism of this order is known to be present when such temperature gradients exist.

nature as nuclear radio sources and not radio jets. Although both radio sources are dominated by unresolved sources, they are slightly extended, particularly the eastern component which has a deconvolved size of 0\".25 along a position angle 55° (Norris 1988). At 6 cm, faint, resolved, emission extends to the south just as in Figure 1. The radio emission is more compact than the infrared, but wherever there is extended radio emission, it is extended in the same direction as the infrared. This applies to the elongation of the eastern and western sources and to the faint broad emission to the south.

The extent of the 2.2 μm radiation is evidence that the flux is not the nonthermal emission from an active nucleus and is most probably dominated by starlight together with some emission from hot (≈ 1000 K) dust. Two further pieces of evidence favor this conclusion: (1) The infrared colors measured in a 2\".5 beam (Carico *et al.* 1990) are very similar to the nuclear colors of the starburst galaxy M82 (Rieke *et al.* 1980); (2) the infrared spectrum of Arp 220 (in an 8\".7 beam) shows deep CO band head absorption at 2.3 μm indicative that the light at this wavelength is dominated by late-type giant and supergiant stars (Rieke *et al.* 1985). Reddened starlight alone cannot account for the observed infrared colors (unless the wavelength dependence of extinction in Arp 220 differs from the Galaxy). An additional component with a color temperature of $T \approx 1000$ K must also contribute to explain the observed colors. The presence of a strong 3.28 μm dust feature in the spectrum of Arp 220 (Rieke *et al.* 1985), which is attributed to very small (10 Å) dust grains, suggests that small grains, heated under nonequilibrium conditions, contribute to the 2.2 μm continuum. If the equivalent width of the 3.28 μm feature is the same in Arp 220 as in Galactic sources (Sellgren 1984), then very small grains probably contribute 20%–30% of the 2.2 μm flux. This fraction of hot dust, together with starlight suffering $A_V \approx 4$ mag, readily accounts for the infrared colors.

From these data a consistent picture of Arp 220 emerges as a merger remnant which still retains two distinct nuclei, both of which contain a dust-enshrouded Seyfert nucleus or quasar, accompanied by circumnuclear starbursts of moderate intensity. This picture explains the compact double radio source, and the bright extended 2.2 μm emission. The correlation of the 2.2 μm light with the low surface brightness radio emission can be attributed to supernovae and their remnants, associated with the starburst, which inject relativistic particles into the interstellar medium enhancing its synchrotron emissivity. The region 290 pc in diameter centered on Arp 220A has an observed $M_K = -21.1$ mag, while the same sized region around Arp 220B has $M_K = -20.6$ mag. These 2.2 μm luminosities should be compared with $M_K = -22.4$ mag observed for the starburst galaxy M82 in a similar sized region. The bolometric luminosity of M82 is $L = 3 \times 10^{10}\ L_\odot$; thus if the extinction in Arp 220 and M82 is similar, then the circumnuclear starbursts in Arp 220 probably account for a only a few percent of its total luminosity. If the extinction toward the stars in Arp 220 is higher than in M82, then a larger fraction of the luminosity can be starburst in origin. However, the hydrogen recombination line Brα is weak in Arp 220 relative to the bolometric luminosity (De Poy, Becklin, and Geballe 1987), suggesting that no more than 10% of the luminosity can be starburst in origin. The width of Brα in Arp 220 (1300 km s^{-1}) is characteristic of active galaxies rather than starbursts, and the line probably originates in a broad line region surrounding an active nucleus rather than H II regions.

The detection of two nuclei in Arp 220 at 2.2 μm adds another double nucleus galaxy to the ultraluminous *IRAS* galaxy sample. Carico *et al.* (1990) have obtained infrared images for nine of the 10 ultraluminous galaxies and have shown that four of the systems have nuclei separated by distances ranging from 2.4 to 6.3 kpc. Thus Arp 220 is remarkable because it has the smallest internuclear separation measured to date. This observation raises three important questions: (1) Do we expect two galactic nuclei to have survived the process of merging and retain distinct identities when separated by only 330 pc? (2) What is the probability of finding such a closely spaced pair when the lifetime of the widely separated systems is ~ 0.2 Gyr (Carico *et al.* 1990)? (3) What is the fate and observational consequences of the merging of two active nuclei?

These questions can be answered by following the merging of two galaxies of mass M and m, where $M > m$. As a smaller galaxy passes through the mass distribution of the dominant galaxy, it looses orbital angular momentum due to the gravitational force of the wake which it leaves behind it, known as dynamical friction, and spirals inward, orbiting at approximately the circular speed v_c for that radius (Binney and Tremaine 1978). At a separation r, the time scale for merging, t_m, is given by the dynamical time scale times the mass ratio,

$$t_m \approx \frac{2\pi r}{v_c}\left(\frac{M}{m}\right). \tag{1}$$

The smaller galaxy is tidally stripped as it spiral inwards and is truncated at the radius where the density of the two systems is comparable. Within the tidal radius, the density distributions are effectively unaltered. The appearance of the nuclei at small separation depends critically upon the density distribution. The nuclear regions ($r \leq 1$ kpc) of nearby galaxies, including the Galaxy, are observed to have isothermal cores described by a power law

$$\rho(r) = \rho(r_0)(r/r_0)^\gamma\ , \tag{2}$$

where $\rho(r_0)$ is the density at some distance r_0, and $\gamma \approx -2$. If the nuclear regions of the merging galaxies have power-law density distributions, then two distinct nuclei will survive until the separation equals the radius where equation (2) breaks down and the density turns over. In the Galactic center the density follows equation (2) with $\gamma = -1.8$ to a radius of 1 pc (Oort 1977), approximately the distance where the dynamics start to be dominated by the central $10^6\ M_\odot$ mass concentration. If the original conditions in the merging nuclei were similar to those at the center of the Galaxy, then the nuclei will remain distinct down to very small separations. The filament which extends from Arp 220A and turns toward B may be tidal in origin, and suggests that this nucleus has just survived a very close (≤ 100 pc) encounter on a highly elliptical orbit. However, as the size of component B is comparable to its tidal radius for the current separation, calculated assuming a mass ratio equal to the 2.2 μm brightness ratio, it seems unlikely that the orbit deviates much from circularity. If this is correct, and the orbit is in the plane of the sky, then according to equation (1) the time for Arp 220 to merge is $t = 1.5 \times 10^7(\sigma/150$ km s$^{-1})^{-1}$ yr, where the velocity dispersion σ typical of galactic nuclei is 150 km s^{-1} (Binney and Tremaine 1987). This is about 4% of the $4 \pm 2 \times 10^8$ yr lifetime of the ultraluminous phase estimated from the occurrence of double nuclei in the ultraluminous *IRAS* sample (Carico *et al.* 1990), and therefore there is a fair probability of catching one of these 10 mergers at this small separation.

To answer the third question it is necessary to describe the ensuing evolution of Arp 220. Let us assume that the far-infrared luminosity of Arp 220 is powered by the double active nucleus, each containing a $\sim 2 \times 10^7\ M_\odot$ Eddington-limited black hole, accreting mass at a combined rate of $\dot{M} = 0.9(\eta/0.1)^{-1}\ M_\odot\ \mathrm{yr}^{-1}$, where η is the conversion efficiency of infall energy. The fuel cannot be stars, because the capture rate is insignificant until the separation of the nuclei reaches a few pc (Roos 1981) but must be the abundant gas present in the system. CO observations demonstrate that there is an ample supply ($9 \times 10^9\ M_\odot$) of gas in the central kpc of Arp 220 (Scoville *et al.* 1986). Bright H_2 emission (Joseph, Wright, and Wade 1984) suggests that cloud-cloud collisions, as well as tidal forces and the nonaxisymmetric potentials of the barred stellar distributions, dissipate the orbital angular momentum. It is the fate of only a small fraction of the gas to find its way onto the nuclear accretion disk; the rest collapses onto the disk which is probably visible as the observed dust lane. The mean free path for cloud-cloud collisions is very small, the slowing down time scale for the clouds is therefore very short, and the gas will settle into a disk in a time of order of one orbit. Thus when merging has completed in $\sim 2 \times 10^7$ yr, and there are no longer any tidal forces, both mechanisms for funneling gas into the nucleus will have switched off because time scales for gas collapse and merging are similar. The subsequent evolution depends upon how much gas is stored in the accretion disk or on orbits which plunge into the nucleus. After merging, $\sim 10^8\ M_\odot$ of gas must find its way into the nucleus, because the lifetime of the ultraluminous phase is estimated to be twice the merging time scale (Carico *et al.* 1990). If the merger is to spawn a dust-free active nucleus or quasar, it is the energy released during this phase which pushes away the enshrouding gas and dust.

Dynamical friction stops shrinking the orbit when the black hole separation is $r_B \approx GM/\sigma^2 = 2(M/10^7\ M_\odot)/(\sigma/150\ \mathrm{km\ s^{-1}})$ pc, because at this point the orbital velocity is greater than σ. If the ultraluminous phase persists after the separation reaches this distance, then accretion continues to cause orbital contraction of the black hole binary on a time scale $M/\dot{M}$ until gravitational radiation takes over at $r_{GR} = 5 \times 10^{15}(M/10^7\ M_\odot)(\dot{M}/M_\odot\ \mathrm{yr}^{-1})^{-0.25}$ cm (Begelman, Blandford, and Rees 1980), at which point evolution proceeds rapidly to coalescence. According to Begelman *et al.*, precession of the black hole binary in the interval $r_B > r > r_{GR}$ can explain the bending and apparent precession of radio jets from quasars including 3C 273. If this is correct, then a black hole binary such as appears to be the final product of a merger such as Arp 220 may be an essential ingredient for many quasars.

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