HIGH-SPATIAL-RESOLUTION, NEAR-INFRARED OBSERVATIONS OF ARP 220

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Received 21 January 1987

ABSTRACT

High-spatial-resolution slit scans of the nucleus of Arp 220 are presented along with near-infrared photometry of the nuclear region. A single nucleus is found coincident with the strongest radio peak. The core is resolved to be on the order of 1″ (370 pc) in diameter. The photometry of the central region shows a minimum near 3.7 μm which is inconsistent with the near-infrared source being a "classical" nonthermal source, such as 3C 273, embedded in a dust cloud.

I. INTRODUCTION

The existence of galaxies with extreme ratios of infrared to blue luminosity and total luminosities on the order of 10^{12} $L_\odot$ is a major discovery of the *IRAS* all-sky infrared survey. It is, however, uncertain whether this luminosity arises in a burst of massive star formation or is the result of a dust-enshrouded nonthermal source in the nucleus; there is evidence that both mechanisms are effective.

Arp 220 = IC 4553 is a prime example of an ultraluminous infrared galaxy (Soifer *et al.* 1984). The bolometric luminosity of Arp 220 is 1.3×10^{12} $L_\odot$ and, as with other luminous infrared galaxies, the galaxy shows distortions and other evidence of large-scale interactions (see, for example, Arp 1966; Sanders *et al.* 1987). The heliocentric velocity of Arp 220 has been determined by Huchra *et al.* (1983) and Mirabel (1982) as $\sim$5400 km s^{-1}, which, for a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1} used throughout this paper, corresponds to a distance to Arp 220 of 77 Mpc.

The principal evidence for a nonthermal source in Arp 220 comes from the properties of spectral lines that are indicative of a Seyfert 2 galaxy; Norris (1985) has summarized evidence for the presence of such a nucleus in Arp 220. More recently, DePoy (1987), for example, has measured a width of 1200 km s^{-1} for the Brackett alpha line, again indicative of an active galactic nucleus. Evidence for starburst activity comes, for example, from Sanders *et al.* (1986) and Scoville *et al.* (1986), who demonstrate the presence of a substantial amount of CO in the nuclear region, while Joseph, Wright, and Wade (1984) argue that the presence of the $S(1)$ line of molecular hydrogen indicates a starburst galaxy. Similarly, Rieke *et al.* (1985) present evidence for a 3.3 μm emission feature and an apparent dominance of the 2.2 μm light by cool stars, both usually associated with starburst models.

One discriminator between these two mechanisms is the spatial extent of the emission, since a burst of star formation would presumably occur throughout much of the central region of the galaxy, while the central nonthermal source is characteristically concentrated within a few parsecs. In this paper we describe near-infrared observations of Arp 220 made with sufficiently high spatial resolution to address these issues.

II. OBSERVATIONS AND RESULTS

Observations were made at the $f/70$ Cassegrain focus of the 5 m Hale Telescope of the Palomar Observatory in June 1985, and April and May 1986. The detector was either a solid-nitrogen-cooled InSb detector with filtering in the standard 1.25 μm (J), 1.65 μm (H), 2.2 μm (K) and 3.7 μm (L') photometric bands, or a helium-cooled germanium bolometer with filtering at 10.1 μm. Cancellation of sky emission was accomplished by "chopping" with the secondary mirror at 5 or 15 Hz and a 15″ north–south throw.

The observations were centered on the position of peak 2.2 μm brightness in a 5″ diameter beam. The coordinates of this maximum, located with an uncertainty of $\pm$ 1″ by offsetting the telescope from the SAO stars 83889 and 83883, were at right ascension = 15^h 32^m 46.83^s and declination = + 23° 40′08″ (1950). This position agrees within 1″ with that of the peak in the radio emission (Condon and Dressel 1978; Baan and Haschick 1984), and within 2″ with the near-infrared determination by Norris (1985).

The photometric observations of Arp 220 were made using different-sized beams and standard infrared photometric systems (Elias *et al.* 1982). These photometric results are given in Table I along with similar observations from Rieke *et al.* (1985). Although the slit scans described below were photometrically calibrated, and agree with the results in Table I, the photometry in Table I is more precise than that obtained with the slit scans, and will be used in the following discussion where flux densities are quoted.

The high spatial resolution was achieved by the use of a 1″×5″ (June 1985) or a 0″.5×5″ (May 1986) slit in the focal plane aligned in an east–west direction. Scans were obtained by smoothly moving the telescope, at rates of one slit width per second, over the source to positions $\sim$5″ north and south of the source. The chopping with the 1″-wide slit was in a north–south direction with an amplitude of 15″, while the chopping with the 0″.5-wide slit was east–west and had a 19″ amplitude. The scans were interleaved with scans

TABLE I. Multibeam photometry of Arp 220.

Beam	Flux density (mJy)[a]					
diameter (″)	1.25 (μm)	1.65 (μm)	2.2 (μm)	3.7 (μm)	10.1 (μm)	Source
3.9	6.6	13.0	18.3			R
4.0	7.0	13.4	18.5	17.4		P
4.6					210	P
5.0	9.2	16.4	21.8	21.9		P
5.8					198	R
7.8	11.4	21.5	24.1			R
8.7	14.4	27.0	30.9			R
10.0	18.8	29.2	33.9	24.7		P

[a] The uncertainties in the Palomar photometry at 1.25, 1.65, and 2.2 μm are less than 5%, those at 3.7 μm are typically 15%, and that at 10.1 μm, 13%.

Notes to TABLE I

Source: P—Palomar observations, this paper; R—Rieke *et al.* (1985).

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of nearby stars in order to obtain the response for a point-like source and to calibrate the observations photometrically.

The scans with the 0″.5-wide slit were made at 2.2 μm over a period of ~50 min when the visual seeing image was ~1″.5 in diameter. The full widths at half-maximum of the profiles of the reference star changed by 0″.1 during the 50 min time of the observation. In the analysis discussed below, these scans, which are shown in Fig. 1, were divided into north- and south-going traversals. The scans made with a 1″-wide slit were obtained in two sets separated by about 40 min, during which time the visual seeing image degraded from ~1″ diameter to ~1″.5 diameter; the visual images were stable during the times each set of observations was made, and the two sets were analyzed separately (see below). The first set of scans was obtained only at 2.2 μm, while scans at 1.25, 1.65, and 2.2 μm were obtained in the second set; these latter scans are shown in Fig. 2. In all cases, the individual traversals were centered by cross correlating them with a scan profile similar to that shown in the figures. The centering was insensitive to the shape of the comparison profile used for the cross correlations.

III. DISCUSSION

Numerous measurements, some contradictory, of the size of the infrared source in Arp 220 have been published. The 60 μm emission, ~100 Jy, must come from a region larger than ~1″ in diameter so that its brightness temperature does not exceed the observed color temperature of 60 K. Joy *et al.* (1986), using the KAO, give upper limits to the nuclear diameter of 7″.5 at 50 μm and 8″.5 at 100 μm. Rieke *et al.* (1985) have concluded that the source is extended on the order of 5–10″ at 10 μm. On the other hand, Becklin and Wynn-Williams (1987), using more extensive observations, find that at 10 and 20 μm the source is less than 2″ in diameter. At 1.6 and 2.2 μm, Norris (1985) finds an unresolved (< 1″) nucleus surrounded by a weak halo. In comparison, Scoville *et al.* (1987) find that the CO emission is concentrated in a region with < 4″ diameter, and the VLA measurements at 1638 MHz of Baan and Haschick (1985) suggest a 1″.3×0″.7 source with a position angle of 98.5°. At visual wavelengths, Norris finds two peaks separated by ~13″ in approximately a north–south line. At the adopted distance to Arp 220 of 77 Mpc, 1″ corresponds to a projected size of 370 pc.

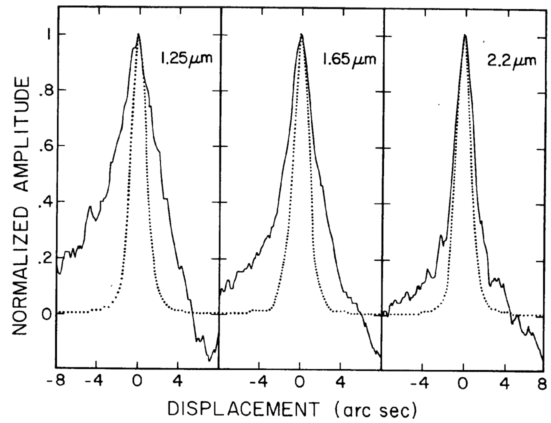

FIG. 2. Slit scans at 1.25, 1.65, and 2.2 μm (left to right) made in June 1985 with a 1″.0-wide slit are shown. The solid curves correspond to scans over Arp 220, while the dotted lines represent similar scans of a nearby star. The profiles of Arp 220 each represent the coaddition of eight traversals over the source. The south-going scans have been inverted in direction, and the profiles have been normalized to unity at their peak values. The asymmetry in the scan profiles is an artifact of the chopping, used to eliminate sky emission, acting on the extended emission.

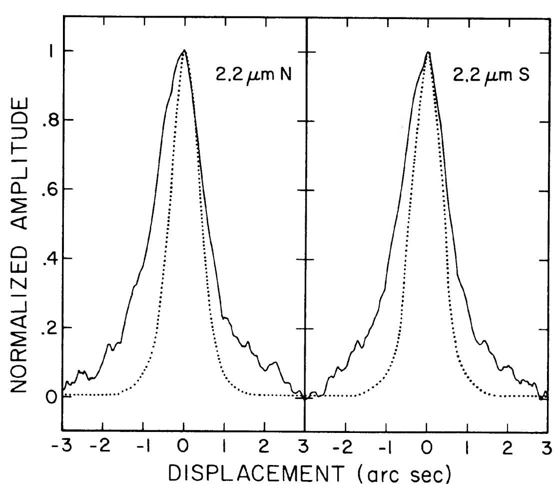

FIG. 1. Slit scans at 2.2 μm made in May 1986 with 0″.5-wide slits are shown. The left-hand profile shows the north-going scans and the right-hand profile shows the south-going scans; the latter have been inverted so both correspond in direction to north-going scans. The solid curves correspond to scans over Arp 220, while the dotted lines represent similar scans of a nearby star. Each profile of Arp 220 represents the coaddition of 80 traversals. For ease in comparison, the profiles have been normalized to unity at their peak values.

Even a cursory examination of Fig. 2 shows that Arp 220 is extended at 1.25 μm and that it apparently contains a compact component at 2.2 μm. The profiles in Fig. 1 show that, with the increased sensitivity to higher spatial resolution provided by the 0″.5 slit, the compact component has, in fact, been resolved. A simple model suggested by the appearance of the profiles is that Arp 220 consists of an underlying galaxy plus a compact, but resolved, source which is prominent at 2.2 μm. This model will be the basis of the following analysis and discussion.

a) Central Source Photometry

In order to evaluate the consequences of the above model, the 1.25 μm flux density in a 4″ diameter beam was assumed to represent purely a "galaxy" component, while the flux densities at longer near-infrared wavelengths were assumed to consist of a galaxy component plus a compact "central" source. The colors of the presumed underlying galaxy component were estimated from the differences in the 4″ and 10″ diameter measurements in Table I, resulting in colors of the galaxy component of [1.25 μm] − [2.2 μm] = 1.26 mag and [1.65 μm] − [2.2 μm] = 0.49 mag. These colors are both substantially redder than those of "normal" galaxies ([1.25 μm] − [2.2 μm] = 0.9 mag, [1.65 μm] − [2.2 μm] = 0.2 mag; Aaronson 1977), but they do, however, lie in the area occupied by other *IRAS* galaxies in a near-infrared color-color plot (see, for example, Carico *et al.* 1986). Physically, the colors are indicative of galaxies with significant reddening or of galaxies that show thermal emission from dust with temperatures ~1000 K. The [2.2 μm] − [3.7 μm] color ~0.1 ± 0.6 mag, consistent with that of normal galaxies ([2.2 μm] − [3.7 μm] ~0.3 mag; Lonsdale, Persson, and Matthews 1984; Glass and Moorwood 1985), but with too large an uncertainty to be in any way definitive.

The flux densities of the presumed galaxy component at 1.65, 2.2, and 3.7 μm were calculated using these assumed colors and then subtracted from the observed flux densities in the 4″ diameter beams. The flux densities of the residual, hereafter termed the "central source," are shown in Fig. 3. There is evidence from several observations that significant amounts of dust, and hence extinction, are present in Arp 220, and the effects of extinction must therefore be considered. For example, Scoville *et al.* (1987) infer a total column density of gas corresponding to a mean visual extinction A_v ~300 mag in the 4″ diameter core of Arp 220 from CO observations, and Becklin and Wynn-Williams (1987) derive $A_v > 50$ mag from observations of the silicate band strength at 10 μm. Optical images also show a dark feature which can be interpreted as a dust lane (see, for example, Sanders *et al.* 1987).

The requirement that the 2.2–3.7 μm spectral index not exceed that of the Rayleigh-Jeans slope sets an upper limit to the 2.2 μm extinction corresponding to A_v ~30 mag. This limit is thus inconsistent with the measurement of the CO gas column unless the measurements at different wavelengths are probing to different depths in the source. The possibility that the slope exceeds the Rayleigh-Jeans limit as a result of emissivity variations in the emission from hot dust grains is discussed below. In order to see if the steep spectral slope is an artifact of the assumptions regarding the galaxy contribution, the photometry of the central component was re-evaluated making the arbitrary assumption that the 1.25 μm flux density within a 4″ diameter beam was due to equal amounts of emission from an underlying galaxy and from a compact central component. The resulting photometry is included in Fig. 3, where it is seen that the color of the central source becomes even bluer between 2.2 and 3.7 μm.

b) Central Source Slit Scans

In order to estimate the size of the central source, it is necessary to separate the galaxy component from the profiles shown in Figs. 1 and 2. As with the photometry, the slit scans at 1.25 μm were assumed to consist purely of a galaxy component, and this profile, scaled according to the galactic colors obtained above, was subtracted from the 2.2 μm profiles to obtain a profile representative of the central source. For the scans with 0″.5-wide slits, the scaled 1.25 μm profile was divided by an additional factor of 2 to account for the 0″.5 versus 1″.0 width of the slits; here the galaxy correction had small effect on the estimated size of the compact source. Clearly, the assumption that the 1.25 μm profile represents only a galaxy component overestimates the galaxy contributions for the central arcsecond at this and the other wavelengths, but including a compact source in the 1.25 μm profile had little effect on the shape of the profile of the central source obtained at 2.2 μm.

As a measure of the size of the central source, the observed central-source profile was assumed to consist of a source with an intrinsic circularly symmetric Gaussian brightness distribution convolved with the response to the reference star. The best least-square fit of the convolved model with the central-source profile for the north-going scans with a 0″.5-wide slit is achieved with a Gaussian source to full width, at e^{-1} the peak value, of 1″.4 ± 0″.3, while the south-going scans gave best fits at 1″.2 ± 0″.2. For both sets of 2.2 μm observations with the 1″-wide slit, the best fits correspond to a size of 1″.0 ± 0″.8. Thus for the combined data, the best fits correspond to a Gaussian source with 50% emission contained within a diameter of 1″.

It is difficult to assess the accuracy of the above estimate, since the true uncertainties result from systematic effects such as variations in the seeing. The uncertainties quoted correspond to an increase by a factor of 2 in the sum of the squares of the differences between the central-source profile and the convolved models. In comparison, the sample dispersion of the size determinations when the sample was divided into eight samples is 0″.2. Tests were made of the sensitivity to the assumed galaxy contribution, which indicate that if no correction were made, the change in the derived diameter is < 0″.2. On the basis of these tests, the estimates given above seem to be accurate for this model. It is reassuring that the observations with 0″.5 and 1″-wide slits give similar results, although the former are clearly definitive.

It is important to realize that the above analysis of central-source profile shapes does not prove that the source has a Gaussian shape; it only gives the size for an assumed Gaussian source. The systematic uncertainties that are present mean that more sophisticated source models are probably not meaningful. Likewise, the analysis cannot establish whether or not the assumption that the 1.25 μm profile consists entirely of galaxy emission is valid. It is also possible

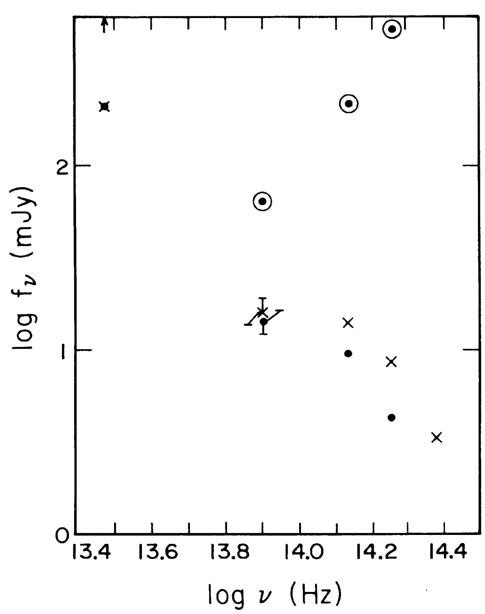

FIG. 3. The continuum energy distribution in the near infrared is shown for the compact core. The dots represent the energy distribution if all the observed flux density at 1.25 μm is galactic, while the crosses indicate the distribution if half the 1.25 μm flux density within a 4″ diameter beam is assumed to come from a compact core. The light circles indicate the dereddened flux density for $A_v = 30$ mag if the extinction law found by Rieke and Lebofsky (1985) applies; the arrow indicates a dereddened flux density at 10.0 μm of ~1900 mJy.

that the galaxy profile changes with wavelength. The extent of the central source is not strongly affected by possible extinction because the procedure of galaxy subtraction is mainly sensitive to the region away from the galaxy nucleus, where the extinction is presumably lower.

c) Contraints on Models of the Central Source

The possibility that the central source is predominantly direct emission from a quasar is ruled out by the fact that the central source is resolved. The hypothesis that the central source represents a dominant quasar is, moreover, inconsistent with the photometric results given in Table I. If the compact source is assumed to have the same ratio of 2.2 μm flux density to total bolometric luminosity as the quasar 3C 273 (assumed to be unreddened) and have a luminosity equal to the bolometric luminosity of Arp 220, the central source would have an unreddened flux density of $\sim$430 mJy at 2.2 μm rather than $\sim$10 mJy; i.e., the 2.2 μm extinction to the core would correspond to $\sim$4 mag or $A_v \sim 40$ mag. An extinction of 4 mag at 2.2 μm implies an extinction of 2 mag at 3.7 μm (Rieke and Lebofsky 1985), or a spectral index between 3.7 and 2.2 μm of the dereddened flux densities of $\alpha(3.7/2.2) \sim +3.0$. This spectral index is steeper than a Rayleigh-Jeans spectrum, and is inconsistent with that of known quasars, which is typically $\alpha(3.7/2.2) \sim -1$. If (see Fig. 3) there is no reddening, the spectral index of the central source is $\alpha(3.7/2.2) \sim -0.8$, but in this case the presumed quasar would provide only 0.02 the luminosity seen in Arp 220. Thus a model consisting of a canonical quasar imbedded in the core of Arp 220, and providing the luminosity and much of the near-infrared flux of Arp 220, is clearly inadequate. An alternate possibility is that the unobserved source of the luminosity is a nonthermal source sufficiently obscured (e.g., with an $A_v \sim 100$ mag) that it is not obvious at 2.2 μm and, possibly, not even at 3.7 μm. The possibility that a central quasar is heating dust to $\sim$1500 K, which is then radiating at 2.2 μm, can be rejected, since the size of such a source must be less than $\sim 0\farcs01$, much less than the observed size.

The core of Arp 220 could also be made up of massive stars in various stages of evolution, as proposed by Rieke *et al.* (1980) for the archetypical starburst galaxy M82. The absolute 2.2 μm magnitude of the core of Arp 220 is $M_K = -22.6$ mag; if this is dereddened for 30 mag of visual extinction, the absolute magnitude is $M_K = -25.6$ mag. For M82, Rieke *et al.* constructed starburst models with the goal of matching the absolute magnitude $M_K = -23.3$ mag with a total luminosity of $4\times10^{10}\,L_\odot$. If these models are scaled to $M_K = -25.6$ mag, they would provide $3\times10^{11}\,L_\odot$, or only about a quarter of the observed luminosity. This agrees qualitatively with the conclusion of Rieke *et al.* (1985) that starburst models, in their present state of development, can account for only 35%–50% of the luminosity of Arp 220. In this connection it is interesting to remember that Telesco *et al.* (1984) have found that about half the luminosity in the Seyfert 2 galaxy NGC 1068 apparently originates in starburst activity.

A different perspective is obtained by noting that if Arp 220 were at the distance of M82, the 2.2 μm flux density observed from the central 400 pc diameter area would be 7.6 Jy. In contrast, the 2.2 μm flux density observed from this area (25″) of M82 is $\sim$2 Jy (Rieke *et al.* 1980). Thus, since the inferred extinction to Arp 220 of $A_v < \sim 30$ mag is comparable to that, $A_v \sim 25$ mag, inferred for M82, the sources would have to be substantially more densely packed in Arp 220 than those in M82 if the core of Arp 220 is composed of sources like those in M82.

Another model capable of explaining the observations is one in which a central, point-like source is heavily obscured along the line of sight, but light emerging in other directions is scattered toward the observer. Such would be the case if there were an optically thick disk surrounding the source, seen more or less edge-on. The situation would be analogous, on a far greater scale, to that in Galactic infrared reflection nebulae (e.g., Castelaz *et al.* 1985). The characteristic size detected in the slit scans is then that of the scattering region combined with the residual flux from the central object. Given the range of possible geometries, it is impossible to evaluate this model realistically on the basis of the existing data. It is, however, clear that if scattering contributes substantially to the 2.2 μm flux from the central source, substantial polarization should be observable. At 3.7 μm, where grain albedos are much lower, there should be much less scattering, and the central point source should be less confused.

The apparent small size at 2.2 μm can be explained as due to a centrally concentrated, heavily reddened stellar distribution, where the effect of the decreased dust absorption at longer wavelengths is to increase the apparent concentration of the center of the galaxy. In this case, the separation into a galactic and a central component as done above is no longer appropriate. The size of 400 pc ($1\farcs2$) discussed above also no longer applies, although the source, presumably a stellar cluster, would be highly concentrated; presumably, it would correspond to unity optical depth at 2.2 μm. The hypothesis of a stellar distribution cannot, however, adequately account for the total luminosity of the galaxy. As noted above, Rieke *et al.* (1985) show that starburst models cannot account for at least half of the galaxy's luminosity. Intuitively, we feel that the distinct appearance of the compact component makes this possibility somewhat *ad hoc*.

IV. CONCLUSION

Evidence for a compact, but resolved, source has been found in the high-luminosity infrared galaxy Arp 220. The intrinsic nature of the source is not understood, since no simple picture fits all the observations and every explanation has well-defined difficulties. Perhaps the easiest explanation is that the compact core consists of stars, seen to wavelengths of 2.2 μm, and a nonthermal, dust-obscured source which is swamped by thermal emission from the surrounding dust at 10 μm. In summary, Arp 220 presents us with a very bright, highly localized core nucleus with a peculiar spectrum. It may be a distinct type of nuclear source. Further measurement of this source and of other high-infrared-luminosity active galaxies are clearly needed to understand its nature.

We thank our night assistant at Palomar, Juan Carrasco, and the entire staff of the Observatory for their help in obtaining these observations. Discussions with Eric Becklin were most stimulating. This work was supported by grants from the NSF.

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