

NEAR-INFRARED MAPPING OF ARP 299 (IC 694-NGC 3690): COLLIDING GALAXIES UNVEILED

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ABSTRACT

We present near-infrared maps and multicolor photometry of the interacting galaxies IC 694 and NGC 3690 which form Arp 299 ($\equiv$ Markarian 171). These data reveal for the first time the distribution of nuclei and old red stars in a cataclysmically interacting system. The nuclei are considerably offset from the visual centroids of the galaxies but not from the mass centroids. The near-infrared colors of the most active regions are strongly affected by extinction, emission from hot dust, and bremsstrahlung. Near-infrared emission is also identified with secondary regions of star formation, probably resulting from the galaxies' interaction.

Subject headings: galaxies: clustering — galaxies: individual — galaxies: structure — infrared: sources

I. INTRODUCTION

Interacting galaxies are often associated with extremely high luminosities and energetic processes (see, e.g., Fischer *et al.* 1983; Joseph, Wright, and Wade 1984; Lonsdale, Persson, and Matthews 1984). The relationship of this activity to the interaction is poorly understood partly because of the very complex morphology resulting from the encounter itself; the visible structure is often so chaotic that it is impossible to locate the galactic nuclei, let alone accurately determine the more extended distributions of stars, gas, and dust.

Because of the reduced extinction compared to that at visible wavelengths, near-infrared observations offer the opportunity to selectively study galaxian components that are otherwise inaccessible. In particular, much of the $2\ \mu\text{m}$ flux from a galaxy is expected to originate in red giant stars that trace the spatial distribution of the oldest and most massive stellar component (Frogel *et al.* 1978). While some studies of the extended near-infrared morphology of individual galaxies are becoming available (e.g., Telesco, Gatley, and Stewart 1982; Stewart 1984), no such observations exist of cataclysmically interacting galaxies. The present study initiates this type of program.

Arp 299 ($\equiv$ Markarian 171 and erroneously listed as Arp 296 in Table 1 of the *Arp Atlas*) consists of the galaxies IC 694 and NGC 3690. These are undergoing an outstanding interaction as manifested by the surrounding filaments and knots (Arp 1966). Strong $10\ \mu\text{m}$ (Gehrz, Sramek, and Weedman 1983, hereafter GSW) and visible-line fluxes from Arp 299 (Weedman 1972; Augarde and Lequeux 1985) have been attributed to an exceptional burst of star formation that may also account for the extended and luminous emission from vibrationally excited H_2 (Fischer *et al.* 1983). Emitting nearly $5 \times 10^{11}\ L_{\odot}$, Arp 299 is also an unusually luminous far-infrared source (*IRAS* 11257+5850; Harper 1984). Short-exposure photographs and the radio and $10\ \mu\text{m}$ maps (Sramek and Tovmassian 1976; GSW) indicate that much of the activity is confined to a few compact regions. The relationship of these compact sources to fundamental galactic structure such as the true nuclei, as defined by the positions of maximum mass, is

unclear; the strongest compact sources in galaxies are not always located at the nuclei, as is well illustrated by the galaxy M82 (see, e.g., Rieke *et al.* 1980).

We have mapped Arp 299 at $2.2\ \mu\text{m}$ and obtained *JHK* photometry at selected positions. These data permit the identification of the galactic nuclei and define fundamental characteristics of the more extended morphology. In doing so, they provide a framework within which to relate the diverse phenomena seen at other wavelengths. Its proximity (42 Mpc for $H_0 = 75\ \text{km s}^{-1}\ \text{Mpc}^{-1}$ and $v_0 = 3155\ \text{km s}^{-1}$; de Vaucouleurs and de Vaucouleurs 1967) and the broad range of energetic phenomena that it exhibits make Arp 299 potentially an exceptionally fruitful hunting ground for clues to the nature of galaxy interactions.

II. OBSERVATIONS

We observed Arp 299 in 1983 November and 1984 April with the InSb detector at the NASA Infrared Telescope Facility.¹ The principal data consist of two maps in the *K* band ($\lambda_0 = 2.20\ \mu\text{m}$, $\Delta\lambda = 0.42\ \mu\text{m}$). The lower spatial resolution map was made with a $7''.6$ diameter beam (FWHM) and covers a region $\sim 1'$ in diameter. The separation between observed positions comprising the map is $\Delta\alpha = \Delta\delta = 5''$. This map is shown in Figure 1 with a visual photograph from Arp (1966); we estimate that the relative positioning of the $2.2\ \mu\text{m}$ and visual maps is accurate to $\pm 3''$. The higher spatial resolution map, which is presented in Figure 2, was made with a $5''.0$ beam with the separation between adjacent data points being $\Delta\alpha = \Delta\delta = 3''$. The map spans a region $33'' \times 18''$ ($\Delta\alpha \times \Delta\delta$) in size. Both maps were made by maximizing the signal on, and offsetting from, source A (GSW). Offsets to A from nearby SAO stars are consistent with the $2\ \mu\text{m}$ peak of A being coincident within $\pm 2''$ with the $10\ \mu\text{m}$ /radio peak in GSW. For these observations the separation between the signal and sky reference positions was either 1.5 or 3.0 in declination. The stars BS 4550 ($J = 4.91$, $H = 4.44$, and $K = 4.38$) and BS 3888

¹ The Infrared Telescope Facility is operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.

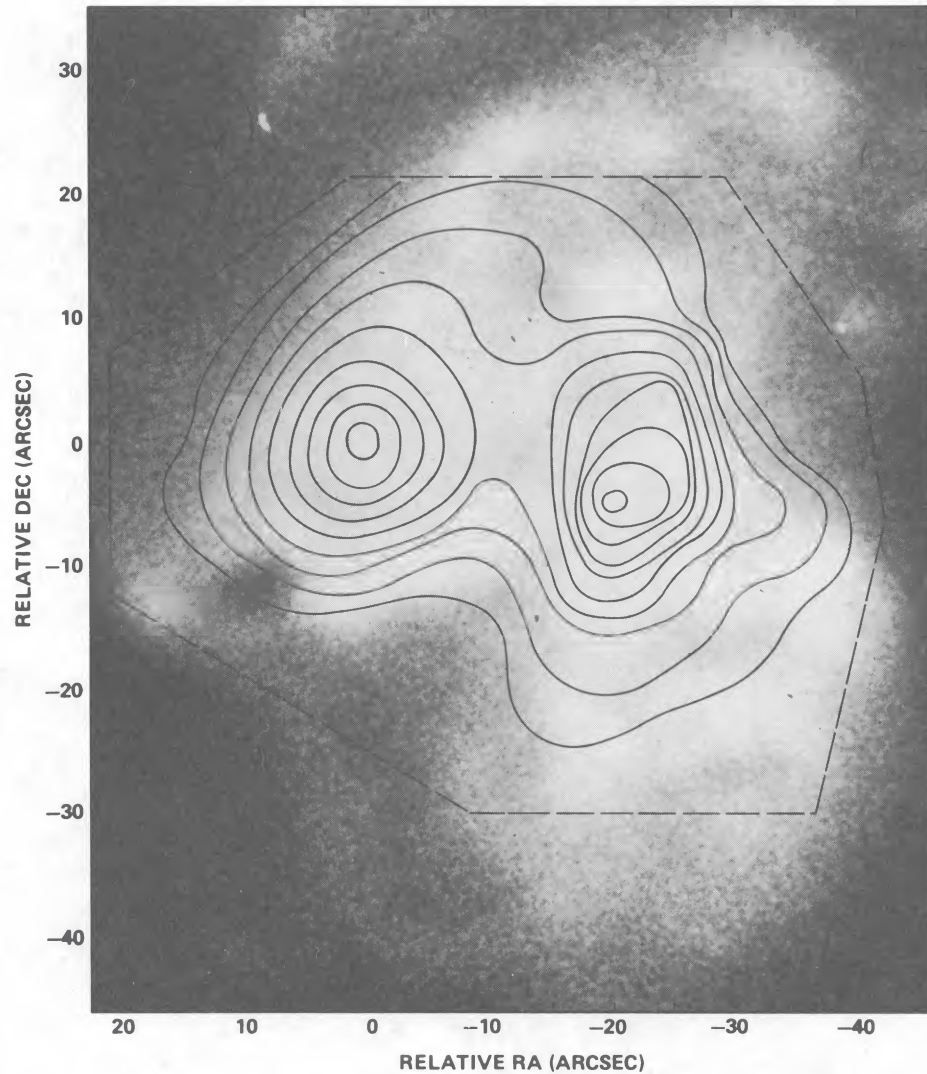


FIG. 1.—The $2.2\ \mu\text{m}$ (K band) map of Arp 299 made with a $7''.6$ diameter beam and shown with a visual photograph from Arp (1966). The lowest contour is 14.2 mag per beam, and the contour interval is 0.4 mag. The statistical uncertainty (one standard deviation of the mean) is typically ± 0.05 mag near the lowest contour and ≤ 0.03 mag elsewhere. The total region mapped is enclosed by the dashed line. The eastern and western $2\ \mu\text{m}$ peaks are identified with the nuclei of IC 694 and NGC 3690, respectively. Coordinates are given relative to source A.

($K = 2.98$) were the photometric standards. We estimate that the absolute calibration is accurate to $\pm 5\%$.

In Figure 3a we present a subset of the data in Figure 1 consisting of scans in declination through sources A and B. The data south of A are replotted in Figure 3b as a function of $r^{1/4}$; filled squares are from Figure 3a. The open squares are from the higher resolution data composing Figure 2 and are normalized by the arbitrary factor of 1.9 to demonstrate their consistency with the $r^{1/4}$ distribution followed by the low-resolution scan.

Additional photometry at $J(\lambda_0 = 1.25\ \mu\text{m}, \Delta\lambda = 0.30\ \mu\text{m})$, $H(\lambda_0 = 1.65\ \mu\text{m}, \Delta\lambda = 0.35\ \mu\text{m})$, and K was obtained at 10 positions along a line through source A and extending from $10''\text{E}$ to $35''\text{W}$ of A. The beam diameter was $5''.0$ with adjacent points separated by $\Delta\alpha = 5''$. Sources B and C (GSW) were also observed. The separation between the signal and reference positions for this multicolor photometry was $1''.5$ in declination. These data are presented in Table 1 and are plotted in the two-color diagram in Figure 4. In this plot the spatial positions, in arcsec relative to source A, are designated within the

TABLE 1
JHK COLORS^a OF ARP 299

Position ^b	$J-H$	$H-K$
A	1.10	0.63
B	0.93	0.61
C	0.79(0.03)	0.99
5	0.95(0.03)	0.36(0.04)
10	0.79(0.04)	0.24(0.06)
-5	0.81(0.04)	0.23
-10	0.83(0.04)	0.22(0.04)
-15	0.77(0.03)	0.36(0.03)
-20	0.68(0.03)	0.56
-25	0.66	0.44
-30	0.68(0.06)	0.32(0.05)
-35	0.71(0.08)	0.11(0.11)

^a Uncertainties are presented in parenthesis when ≥ 0.03 mag.

^b Numbers are R.A. offset in arcsec relative to Source A.

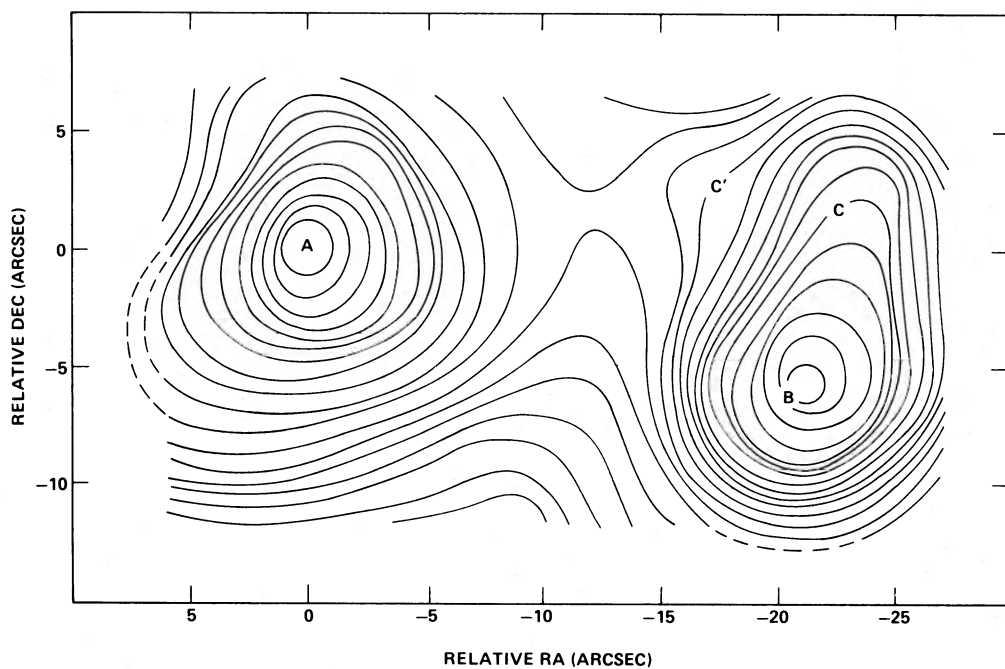


FIG. 2.—The $2.2\ \mu\text{m}$ map of Arp 299 made with a $5''.0$ diameter beam. The lowest contour (*bottom center*) is 14.6 mag per beam, and the contour interval is 0.2 mag. Peak contours are 11.2 mag per beam at A and 10.8 mag per beam at B. Statistical uncertainties are ≤ 0.03 mag everywhere. Letters designate regions discussed in text and by GSW. Coordinates are given relative to source A.

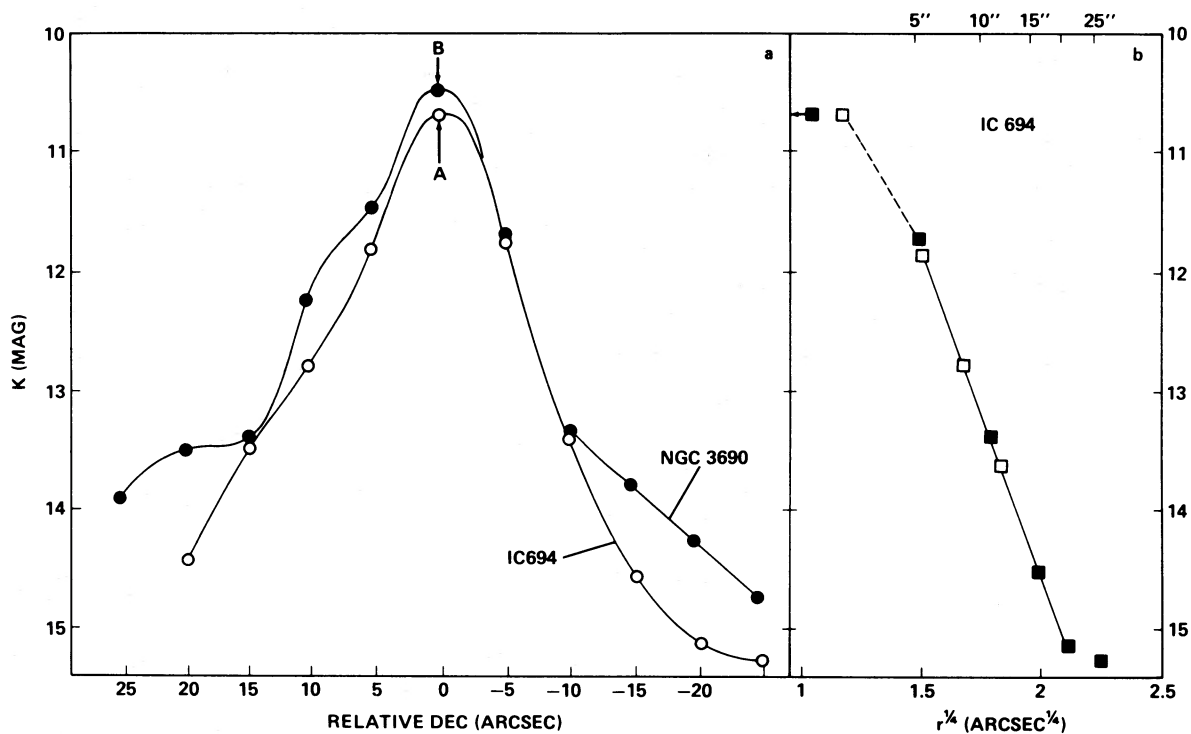


FIG. 3.—(a) K scans in declination through sources A and B, the nuclei of IC 694 and NGC 3690, respectively. These data are a subset of those composing the map in Fig. 1. (b) K scan south of source A plotted as a function of $r^{1/4}$. Filled squares are from Fig. 3a. Open squares are data from Fig. 2 ($5''$ beam), arbitrarily normalized to demonstrate their consistency with the $r^{1/4}$ distribution followed by the lower resolution data.

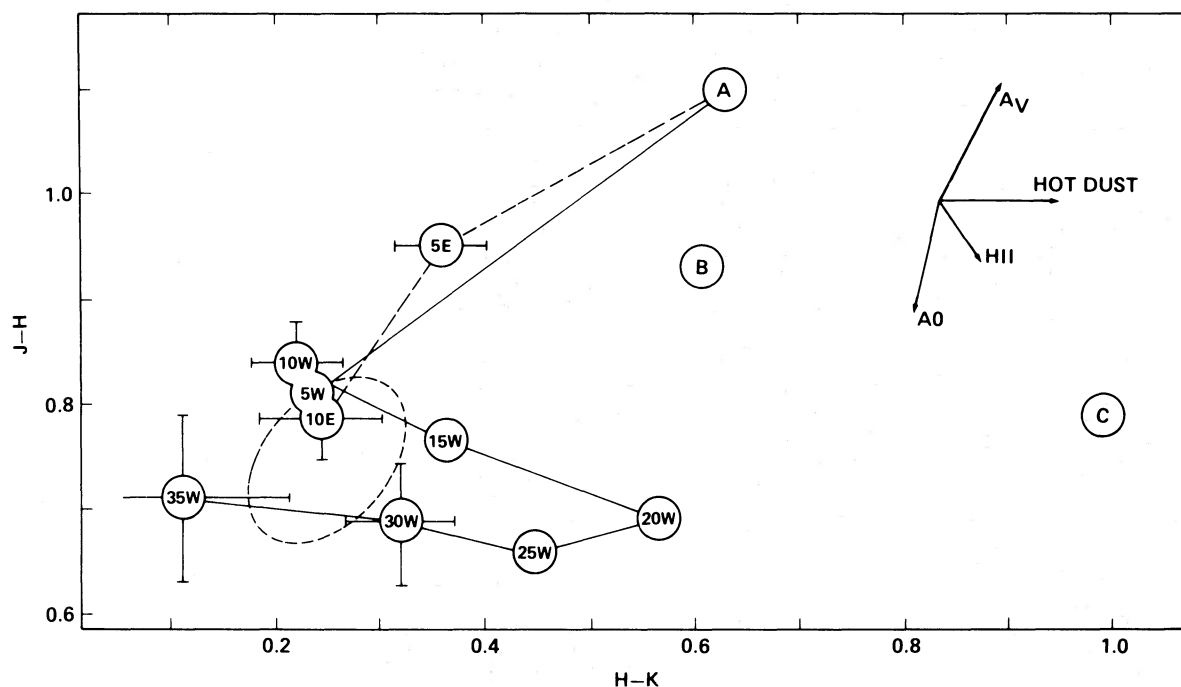


FIG. 4.—Two-color observations of Arp 299 made with a $5''.0$ diameter beam. Solid and long-dashed lines connect colors for positions along scans extending westward and eastward, respectively, from source A. Positions in arcsec relative to source A are designated within the corresponding circles. Colors for sources A, B, and C from Fig. 2 are designated explicitly. The region within the short-dashed ellipse is that occupied by the nuclei of most elliptical and spiral galaxies, for which the $2\ \mu$ light is primarily from red giants (Frogel *et al.* 1978). The vectors (see Telesco and Gatley 1984) indicate how the red giant colors are affected by blue stars ("A0"), bremsstrahlung emission ("H II"), emission from 500 K dust with emission efficiency varying linearly with frequency ("HOT DUST"), and 1 mag of visual extinction ("A_v"); the vector length for A0, H II, and hot dust represents the displacement expected if that process contributes 10% of the total $2.2\ \mu$ flux density.

corresponding open circles. The $10\ \mu$ /radio peaks A, B, and C are denoted explicitly.

III. RESULTS

a) Morphology

i) General Description

Figure 1 shows that there are two $2\ \mu$ peaks in Arp 299. We interpret these peaks as the nuclei of the galaxies IC 694 (eastern peak) and NGC 3690 (western peak). The large spatial coverage of our map and the approximate concentricity of the lower level contours with the peaks imply that they are the galactic nuclei and not simply isolated emission regions or superposed Galactic field stars. The nuclei are separated by $\sim 21''$, or 4.3 kpc in projection. While some uncertainty has existed about whether Arp 299 is an interacting pair or a single disrupted galaxy (e.g., Allen 1976; Bushouse and Gallagher 1984), our observations firmly establish it as a system of two galaxies. Based on previous multiaperture photometry (Frogel *et al.* 1978) and mapping of galaxies (Telesco, Gatley, and Stewart 1982; Stewart 1984; Telesco and Gatley 1984), it is most probable that the $2\ \mu$ emission originates primarily in the photospheres of red giant stars (Frogel *et al.* 1978) that are tracers of the distribution of older stars constituting most of the galaxian mass. Our multicolor photometry (§ IIIb) supports this assumption. However, as discussed below, other processes such as emission from hot dust contribute to the $2\ \mu$ flux, probably resulting in some of the observed structure in the map.

Figure 1 permits comparison of the lower resolution $2\ \mu$ map with the blue/visual photograph from Arp (1966). The overall $2\ \mu$ distribution is seen to bear some resemblance to

the visual one. However, both nuclei are noticeably displaced from the centers of the visual images usually identified as IC 694 and NGC 3690. The nucleus in IC 694 is displaced $\sim 10''$, or 2.1 kpc in projection, SE along the elongated image, or "major axis." The nucleus of NGC 3690 is displaced northward by $\sim 15''$, or 3.1 kpc, from the visual centroid of that galaxy, and coincides approximately with the apparent visual point of contact of the two galaxies. Condon *et al.* (1982) and Sramek and Tovmassian (1976) noted qualitatively similar offsets of the brighter radio and visible knots relative to the visual centroids of these galaxies.

We see from Figure 3a that there is no deficiency of flux north of B compared to the south, in contrast to the impression derived from the visual appearance that the nucleus of NGC 3690 is off center. We conclude that the galaxies overlap in the northern part of Arp 299, and that much of the increased $2\ \mu$ brightness in this region is due to this superposition.

In the higher resolution $2\ \mu$ map (Fig. 2) we have indicated the positions of sources B, C, and C' as determined relative to source A from the radio continuum observations by GSW. In light of the above discussion, we identify A and B with the nuclei of the galaxies IC 694 and NGC 3690, respectively. Sources C and C' coincide with $2\ \mu$ shoulders. Source d of GSW, which is about $5''$ south of A and is not indicated in Figure 2, has no obvious $2\ \mu$ counterpart. GSW's region e coincides with the $2\ \mu$ "bridge" extending in R.A. near the center of the map, and, at least at $2\ \mu$, may result simply from the superposition of the emission from the two galaxies. Figures 1 and 2 indicate that the nuclei are comparable in brightness at $2.2\ \mu$, as they also are at 12 and $23\ \mu$ (GSW). However, at 6 and $20\ \text{cm}$ (GSW) and $100\ \mu$ (Harper 1984; see below), source A is many times stronger than B. Nucleus A also

apparently dominates the Br γ and H $_2$ emission (Fischer *et al.* 1983), although the observations do not accurately determine the locations of the emitting regions.

ii) *The Individual Galaxies*

Any comparison of the morphology of the individual galaxies in an interacting system to that observed for normal galaxies must be viewed with caution. However, it may lead to a better understanding of the precollision types of the galaxies and hence of the interaction itself. In Figure 3b, which incorporates data from both 2 μ m maps, we see that south of source A the 2 μ m brightness follows an $r^{1/4}$ distribution out to 20", or 4 kpc. The scans extending from A and with P.A. = 45°, 90°, and 135° are consistent with this conclusion, although only that at P.A. = 90° extends to 20". Scans extending northward and northeastward of A exhibit substantial emission in excess of this $r^{1/4}$ distribution, due at least partly to the overlap in the brightness distribution of the two galaxies. Therefore, it appears that the red giants, and therefore probably most of the mass, coinciding with the southeastern half of IC 694 are spatially distributed like those in elliptical galaxies and the bulges of disk galaxies (see, e.g., Kormendy 1977). The slight turn-up in brightness at 25" south of A may correspond to the emergence of a disk beyond 4 kpc in IC 694, but the proximity of NGC 3690 makes that interpretation ambiguous. While it is tempting to identify the elongated visual image extending SE–NW with the dusty disk of IC 694, the offset location of the nucleus implies that much of the visual elongation is due either to the distortion of gas and dust by the two-galaxy interaction or to the superposition of emission from gas and stars associated with NGC 3690. Certainly the latter is important to some extent as indicated by the higher 2 μ m brightness there. We conclude that the existence of a disk for IC 694 remains uncertain. The possibility that the bulge of IC 694 dominates the K light out to $r > 4$ kpc from the nucleus suggests that this galaxy may be (or may have been) of Hubble type Sb or earlier; for comparison, the bulge light of the Sb galaxy M31 dominates along its major axis out to ~ 6 kpc (de Vaucouleurs 1958).

In contrast to IC 694, the 2 μ m brightness distribution south of the nucleus of NGC 3690 exhibits what can be straightforwardly interpreted as an exponential-like disk at $r > 10''$, or 2 kpc (Kormendy 1977). Furthermore, although the 2 μ m nucleus of NGC 3690 appears to be offset northward from the main body of the visible galaxy, there is sufficient near-infrared emission north of B, as indicated in Figure 3, to accommodate a disk component like that seen to the south (§ IIIa).

The total 2.2 μ m flux density of Arp 299 from the region mapped in Figure 1 is 229 ± 20 mJy. The uncertainty includes that in absolute calibration ($\pm 5\%$) and inaccuracies in the determination of the beam profile. If, as discussed in § IVb, we assume that the southeast part of IC 694 is undistorted by the interaction and symmetric about its nucleus, the total 2 μ m flux density from IC 694 is ~ 90 mJy, or about 40% of the total. Therefore, assuming that the 2 μ m flux traces the most massive stellar component, IC 694 and NGC 3690 have comparable total masses within the mapped region.

b) *Color Variations*

Arp 299 exhibits large spatial variations in its near-infrared colors, as shown in Figure 4. The region within the dashed ellipse is that occupied by the nuclei of most elliptical and spiral galaxies, for which the near-infrared radiation originates mainly in red giants (Frogel *et al.* 1978). It is evident that most

of the points are in or near this ellipse. However, large displacements of the colors from those typical of normal galactic nuclei are observed for the nuclei A and B and especially for source C. Certain trends in the color variations are also apparent; as the scan proceeds westward from A, $H-K$ becomes first redder—being reddest at 20"W—and then bluer, while $J-H$ becomes systematically bluer.

Figure 4 shows the displacements expected (see Telesco and Gatley 1984) when normal nuclear colors are modified by interstellar extinction (" A_v "), emission from hot dust, thermal bremsstrahlung (" $H\ II$ "), and blue stars (" $A0$ "). In general, the colors do not uniquely define which of these processes dominates the emission. For example, the colors of an $H\ II$ region with heavy extinction are similar to those indicative of hot dust. Despite this ambiguity, when considered together with other observations the near-infrared colors can significantly constrain models which describe Arp 299.

i) *Source A*

Fischer *et al.* (1983) observed spatially extended Br γ line emission from Arp 299. Their observations were made with two different beam sizes, one encompassing the sources A, B, and C and the other including only B and C. If the difference in the observed fluxes in these two beams is attributable to A, the corresponding Br γ flux is $(1.6 \pm 0.5) \times 10^{-13}$ ergs $\text{cm}^{-2} \text{s}^{-1}$. For a 10^4 K gas, the ratio of the 2.2 μ m continuum flux density (bound-free, free-free, and two-photon emission) to the Br γ line flux is $3.7 \times 10^{-13} \text{ Hz}^{-1}$. Therefore, the contribution by the thermal gas at the nucleus A to the observed 2.2 μ m flux density is 5.9 ± 1.8 mJy, corresponding to $24\% \pm 7\%$ of the total observed there in a 5" beam. We conclude that the difference in the observed colors at A and those of normal giant-dominated nuclei can be produced by the combination of bremsstrahlung emission implied by the Br γ flux and 4.6 mag of intervening visual extinction. This is illustrated in Figure 5. While some ($< 5\%$) of the near-infrared radiation can be emitted by hot dust, we find that bremsstrahlung emission and especially extinction are the dominant processes modifying the near-infrared colors of the nucleus of IC 694.

It should be noted that our extinction estimate for source A is higher than the value $A(H\beta) \approx 3$ determined from the Balmer decrement by Augarde and Lequeux (1985), but possibly consistent with the much fainter emission observed there by GSW. The large extent of the visual emission near A (see Fig. 2 in GSW) and the corresponding positional ambiguity may account for discrepancies among the visual results, as noted by Augarde and Lequeux (1985). Visual fluxes are also heavily weighted by emission from the least obscured regions included within the beam. In addition, the extinction determined from the near-infrared continuum colors (Fig. 5) is an average value to the giant stars distributed across the central ~ 1 kpc (although undoubtedly weighted toward the peak nuclear emission), whereas infrared and visual emission lines more nearly reflect the obscuration local to the line-emitting region. Finally, as pointed out by GSW, the 10 μ m silicate absorption feature at source A implies $A_v \approx 24$ which may be largely indicative of extinction to infrared sources embedded within molecular clouds. In short, these complications must be kept in mind when drawing conclusions based on extinction estimates.

ii) *Sources B and C*

GSW have observed H α and H β line emission from sources B and C that implies visual extinctions of 1.8 and 1.6 mag,

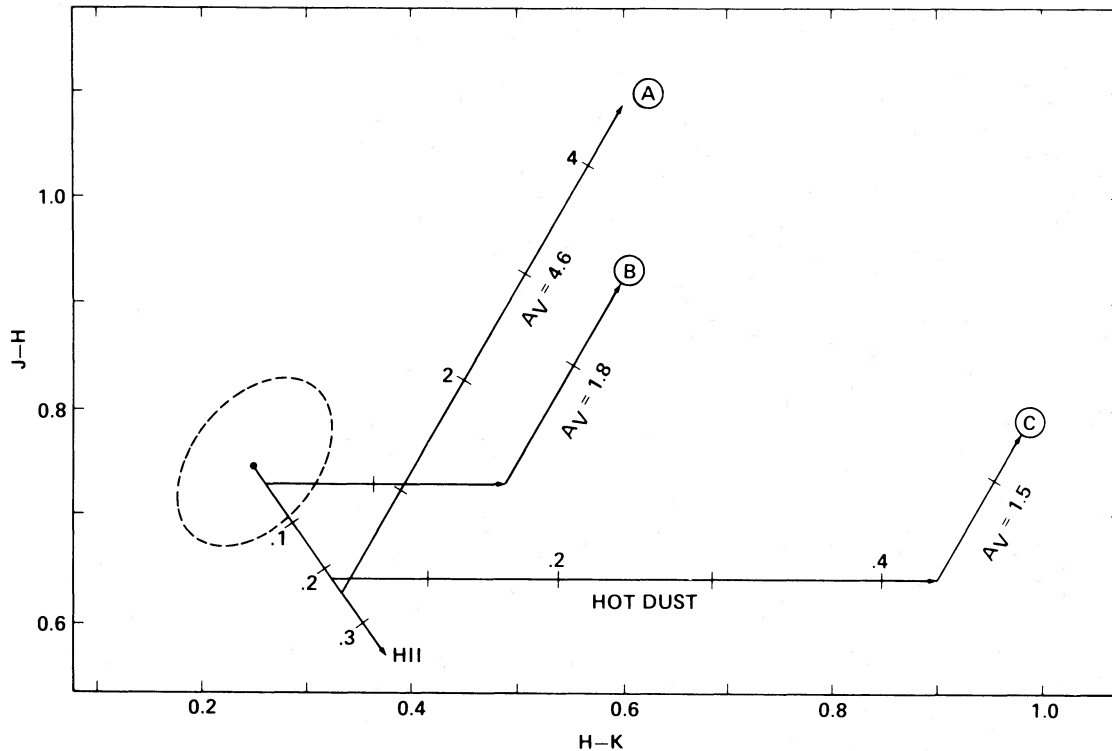


FIG. 5.—Two-color plot showing explicitly how the colors of sources A, B, and C result from the modification of red giant colors by the indicated processes. Tick marks on vectors show the vector magnitude when the process contributes the indicated fraction of the total $2.2 \mu\text{m}$ flux.

respectively. These and the infrared data fit into a reasonably consistent picture describing sources B and C. The total $\text{Br}\gamma$ line flux from the vicinity of B and C is $(1.0 \pm 0.12) \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (Fischer *et al.* 1983), for which the corresponding $2.2 \mu\text{m}$ bremsstrahlung emission is $3.7 \pm 0.5 \text{ mJy}$. If this flux originates from each source in proportion to its extinction-corrected $\text{H}\alpha$ flux, then the $2.2 \mu\text{m}$ bremsstrahlung contributes 4% and 20% of the total K light at B and C, respectively. The corresponding displacements along the H II vector are shown in the two-color plot in Figure 5. We also show the extinction vectors for the two sources, based on the data of GSW. Figure 5 implies that emission from hot dust makes a significant contribution to the near-infrared flux from the nucleus B ($\sim 20\%$) and especially to that from the extranuclear source C ($\sim 43\%$).

The red $H-K$ colors at $20''$ and $25''\text{W}$ (Fig. 4) are intermediate between those of source C and those for red giants. Because these locations are only a few arcseconds away from C, it is probable that the emission from hot dust evident at C also affects their colors. In fact, the values of the near-infrared flux at $20''$ and $25''\text{W}$ are noticeably fainter than the flux at C, and the presence of C in the wings of the beam at these two locations is likely to dominate their color excursion toward C in Figure 4. The unique colors of C, as well as those of A and B, suggest that the activity causing the most prominent color variations is largely confined to several relatively compact regions (each with diameter $\lesssim 5'' \equiv 1 \text{ kpc}$) rather than being widespread. Interestingly, the $J-H$ colors from $20''$ to $35''\text{W}$ are noticeably bluer than that of C. The color vectors in Figure 4 suggest that this blueing trend is due either to a reduction in interstellar extinction ($\Delta A_v \approx 1$ compared to source C), or to

an admixture of blue stars emitting $\sim 10\%$ of the K light at those positions. The present data do not permit us to choose between these alternatives.

Our estimate of the fraction of the $2.2 \mu\text{m}$ flux originating in dust, combined with the $12.6 \mu\text{m}$ flux measurements by GSW, permit us to determine blackbody color temperatures for the highest temperature dust in A, B, and C. The flux density at $12.6 \mu\text{m}$ was chosen since that wavelength is outside the spectral region dominated by the $10 \mu\text{m}$ "silicate" feature detected by GSW. The flux densities, their ratios, and the corresponding dust color temperatures are presented in Table 2. These data imply that near-infrared emitting dust at C is noticeably hotter than that at B, which is hotter than that at A. The cooler appearance of A may result partly from the high extinction there. Correcting the $2.2 \mu\text{m}$ flux limit for extinction ($A_K = 0.1 A_V$) implies a flux ratio in Table 2 of > 680 , or a color temperature $< 465 \text{ K}$.

TABLE 2
DUST COLOR TEMPERATURES

Source	F_v^a ($2.2 \mu\text{m}$)	F_v^b ($12.6 \mu\text{m}$)/ F_v ($2.2 \mu\text{m}$)	T^c (color)
A	< 1.2	> 1040	< 450
B	6.6 ± 2	239 ± 75	$510 (+20, -15)$
C	5.1 ± 2	76 ± 36	$575 (+40, -25)$

^a Flux density in mJy attributed to hot dust, as determined from Figs. 2 and 5.

^b Flux density at $12.6 \mu\text{m}$ from GSW, Table 2. Ratio applies to $5''$ diameter region.

^c Blackbody color temperature, in K.

IV. DISCUSSION

a) *The Compact Sources*

The most important observational results of this study are the location of the nuclei of the two galaxies that constitute the interacting system Arp 299 and the determination of the extended near-infrared morphology. GSW and others have argued convincingly that Arp 299 is experiencing an outstanding burst of star formation that may have resulted from the interaction. Our observations therefore establish that the most intense activity associated with young stars is mainly occurring at, or very near, the nuclei. The $10\ \mu\text{m}$ and radio maps (GSW; Sramek and Tovmassian 1976), especially those that include large regions surrounding the compact sources A, B, and C, show little intense activity away from the nuclei, a picture supported by shorter exposure photographs (Morgan 1958; Sramek and Tovmassian 1976; Bushouse and Gallagher 1984). The one major exception is source C itself, possibly a giant extranuclear H II region, which is separated from the nuclear source B by $8''$, or 1.6 kpc in projection. While the proximity of C to B makes it tempting to associate C with NGC 3690, C is located in the region of overlap of the two galaxies. If the activity at source C is a by-product of the galaxies' interaction, it may not be physically meaningful to associate it with either galaxy.

Particularly intriguing is the indication that hot dust is relatively more important in C than in B and in B than in A. Strong evidence for a cooler component of dust in A is also provided by the observation that A emits at least 80% of the large far-infrared luminosity of $4.9 \times 10^{11}\ L_{\odot}$ originating in the central $50''$ (Harper 1984) even though A and B emit comparable $10\ \mu\text{m}$ fluxes.

The combined far-infrared luminosity of B and C is $<20\%$

that of A (Harper 1984). The extinction-corrected Bry flux for B and C is $\sim 50\%$ that from A. In Figure 6 we show how N_i/L , the Lyman photon production rate per unit total luminosity, depends on the burst age T_0 for bursts of star formation with $T_0 \approx 10^6$ – 10^9 yr. These calculations (Telesko and Gatley 1984) apply to starbursts that are uniform in time and have stellar initial mass functions (IMFs) extending up to $30\ M_{\odot}$ and $60\ M_{\odot}$; these results are relatively insensitive to the lower mass cutoff. For source A the ratio is $N_i/L = 9.4 \times 10^{42}\ \text{s}^{-1}\ L_{\odot}^{-1}$, which corresponds to $T_0 \approx 10^9$ yr for an upper mass cutoff of $60\ M_{\odot}$. For B and C together, $N_i/L > 2.1 \times 10^{43}\ \text{s}^{-1}\ L_{\odot}^{-1}$, corresponding to $<3 \times 10^7$ yr; the limit (indicated by the arrow in Fig. 6) reflects the constraint on L for B and C. If the starburst IMF has an upper mass limit of $<60\ M_{\odot}$, the inferred burst ages are smaller; for a limit as small as $30\ M_{\odot}$, Figure 6 implies that $T_0 < 3 \times 10^6$ yr for NGC 3690 and 2×10^7 yr for IC 694. The uncertainties in such an analysis are admittedly large (extinction corrections being particularly critical; see § IVb), but the models do suggest that a large difference in the ages of the bursts of star formation IC 694 and NGC 3690 can account for the relative ionization rates. Furthermore, the higher dust temperatures could result from the increased Lyman- α heating of the dust in the younger bursts.

b) *Other Regions of Activity*

Even though the most intense young star activity is associated with the two nuclei and source C, lower level activity is evident throughout Arp 299 as blue knots and filamentary structure (Fig. 1). Are these less active regions seen in our infrared data? To examine this we have subtracted the $2\ \mu\text{m}$ brightness distribution of IC 694 from our lower resolution map under the assumption that IC 694 is symmetric about its

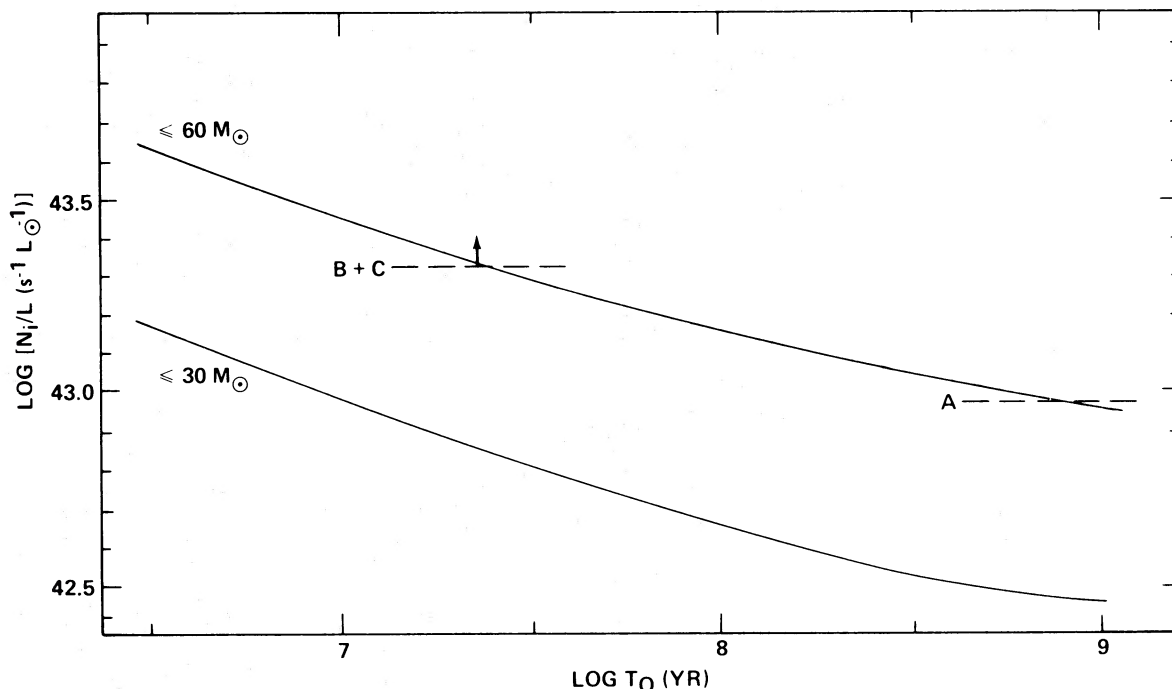


FIG. 6.—Ionizing photon rate per unit luminosity expected for an episode of star formation that has proceeded at a uniform rate for a time T_0 (Telesko and Gatley 1984); starburst models use solar neighborhood initial mass functions extending up to 30 and $60\ M_{\odot}$. Dashed lines indicate ratios determined for source A and sources B and C together. The dashed line for B + C corresponds to the limit on far-infrared emission from those sources.

nucleus and that the flux to the east and southeast are attributable solely to that galaxy (§ IIIa); these “undisturbed” regions (see, also, Augarde and Lequeux 1985) are spanned by a line from the nucleus A and sweeping through P.A. $\approx 45^\circ$ – 180° . The residual flux is shown in Figure 7. Because of the limited extent of the IC 694 data, the subtraction was made only for the region to the left of the dashed line in Figure 7; while not negligible, the contribution of IC 694 to the right of that line should be small enough not to affect our conclusions.

Figure 7 implies that there may be two major near-infrared-emitting regions of lower level activity in Arp 299. The most important of these is north of the primary compact sources A, B, and C, and occurs where the two galaxies most nearly overlap. This region is roughly 4 kpc in projection from A and B. The second region is west of source B. This region, of course, is not affected by the subtraction process but does show up more clearly in Figure 7. It should be kept in mind that from these data alone we cannot distinguish between surface brightness variations due to, for example, young star activity and actual distortions in the stellar distribution that result from the galactic interaction. It is noteworthy, however, that the $10\ \mu\text{m}$ map by GSW shows an extension to the southwest from B. In addition, their 20 cm maps, especially that with the larger spatial coverage, show radio continuum emission extending into both of the secondary centers of activity. It seems likely,

then, that these regions evident in our maps are locations of recent star formation. If the $2\ \mu\text{m}$ brightness irregularities do result from local enhancements in the star formation rate, our observations elsewhere in Arp 299 suggest that the radiation from these regions in excess of that from red giants is from hot dust, blue stars, or ionized gas. Available data are insufficient to determine which is the most significant. We conclude that while the most intense activity is confined to a small number of locations, most notably the nuclei, the burst of star formation probably resulting from the galaxy interaction may be evident at a much lower level in the infrared throughout much of Arp 299.

c) The Interaction

Theoretical and observational analyses (e.g., Toomre 1977; White 1978; Condon *et al.* 1982) suggest that interactions between galaxies can be very inelastic, leading to a large increase in their internal energy, rapidly decaying orbits, and mergers. Intense star formation may be one major consequence of this redistribution of matter and energy. The knots and filaments evident in the visual photographs of Arp 299 are convincing evidence that IC 694 and NGC 3690 are interacting galaxies and not just a chance superposition. The large infrared luminosity and substantial emission from H_2 support this

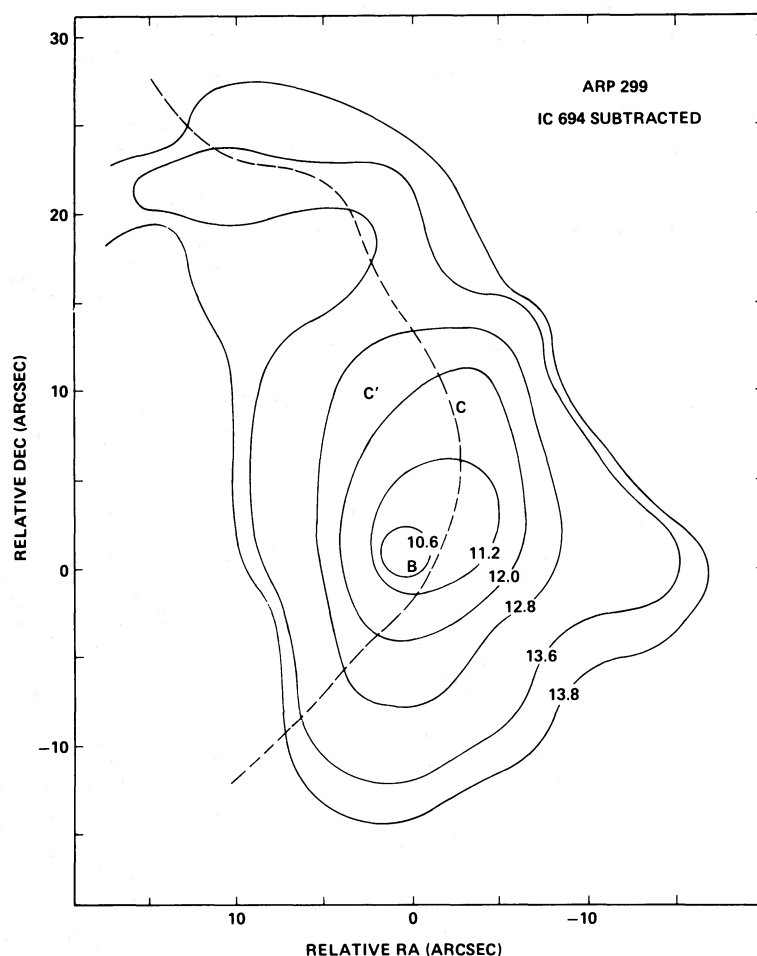


FIG. 7.—Map at $2.2\ \mu\text{m}$ resulting from subtraction of IC 694 from data in Fig. 1. Only that region east of dashed line is affected by subtraction. Note nonuniform contour intervals (magnitudes). Coordinates are given relative to source B.

view, although the relationship of these phenomena to the interaction is not understood.

Our results provide a basis for further speculation about the nature of Arp 299. Our starburst models imply a difference of more than a factor of 10 in the ages of the bursts of star formation in the two galaxies. For an initial mass function extending to $60 M_{\odot}$, the age of $\sim 10^9$ yr for the burst in IC 694 (Fig. 6) is comparable to the orbital period of a binary system with components of mass $\sim 10^{11} M_{\odot}$ and a relative velocity of a few hundred kilometers per second. This mass is reasonable for a normal galaxy, and the velocity is consistent with the observed relative radial velocity of $\sim 100 \text{ km s}^{-1}$ (de Vaucouleurs and de Vaucouleurs 1967). Thus, the starburst in IC 694 (i.e., source A) may have been initiated by the *previous* close encounter of these two galaxies, with the activity in NGC 3690 resulting from the current encounter. However, Augarde and Lequeux (1985) have recently estimated a total mass for Arp 299 of only $\sim 4 \times 10^{10} M_{\odot}$, with the initial mass function extending to $\sim 35 M_{\odot}$. These parameters imply a burst age of a few times 10^7 yr for source A, much smaller than the corresponding orbital period.

In any case, if the actual separation of the two galaxies is comparable to the projected separation of their nuclei (4 kpc), the current encounter may be their last; slow encounters are "sticky," and in cases where mass distributions overlap significantly, a merger is expected in only a few orbital periods (White 1978; van Albada and van Gorkom 1977; Toomre 1977). Therefore, IC 694 and NGC 3690 are possibly merging. The tidal forces may therefore be sufficient to noticeably distort the most massive stellar component, thereby producing some of the irregular structure evident in our $2 \mu\text{m}$ maps.

V. SUMMARY AND CONCLUSIONS

We have obtained the first near-infrared maps of an interacting galaxy system, Arp 299. Our observations indicate the following:

1. The nuclei of the galaxies of IC 694 and NGC 3690, which constitute Arp 299, are considerably offset from the visual centroids of the galaxies. However, they are not significantly offset from the mass centroids determined from the near-infrared maps.
2. The two strongest regions of activity evident at other wavelengths are found to coincide with the nuclei, while a third region is not clearly identifiable with either galaxy.
3. The near-infrared colors of nuclear source A are substantially modified by ~ 5 mag of interstellar extinction. The colors of the nuclear source B and especially the extranuclear source C are strongly influenced by emission from hot dust and, to a lesser extent, extinction and bremsstrahlung emission. The near-infrared colors of these sources are among the most extreme yet observed for extragalactic objects.
4. The $2 \mu\text{m}$ morphology of IC 694 resembles that of an elliptical galaxy or the bulge of a disk galaxy. No evidence for a disk is seen within the region mapped. The morphology of NGC 3690 resembles that of a disk galaxy.
5. Based on simple models describing a burst of star formation, the dust temperatures and the ionization rate per unit luminosity are consistent with the age of the starburst in NGC 3690 being significantly younger than that in IC 694.
6. We identify two secondary regions of activity in Arp 299 which may correspond to additional sites of star formation resulting from the galaxy interaction. Alternatively, this structure in the brightness distribution may be a distortion in the stellar distribution that results from the interaction of the galaxies.

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