INFRARED EMISSION REGIONS IN THE INTERACTING GALAXY SYSTEM ARP 299

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ABSTRACT

We present infrared imagery and photometry of the interacting galaxy system Arp 299 (also called Markarian 171, or NGC 3690/IC 694). In the central region of NGC 3690 we see two 2.2 μm sources; one of these (component B2) coincides with the apparent visible nucleus, while the other (component B1) coincides with the 6 cm and 10 μm sources. We see no evidence at 2.2 μm for a compact AGN in IC 694 (component A). Approximately 75% of the 12–25 μm power from Arp 299 comes from three regions each smaller than 600 pc in diameter centered on components A, B1, and C, making the distribution of mid-infrared emission more concentrated than the distribution of starlight. We remain ambivalent as to whether or not source C marks the position of a further galaxy nucleus. It is more luminous than any known nonnuclear astronomical object and has physical conditions even more extreme than those in well established starburst nuclei. The main arguments against its being a nucleus are based on the implausibility of multiple simultaneous mergers.

Subject headings: galaxies: individual (Arp 299) — galaxies: interactions — galaxies: structure — infrared: sources

1. INTRODUCTION

The system of interacting galaxies NGC 3690/IC 694 (aliases are Arp 299 and Markarian 171) is an important one to understand for a number of reasons. First, at a distance of 42 Mpc (assuming H₀ = 75 km s⁻¹ Mpc⁻¹), it is one of the nearer examples of a possibly merging system. Second, its 60–100 μm luminosity—5 x 10¹¹ L₀ (Soifer et al. 1987)—puts it among the most powerful galaxies known, with an infrared luminosity at least 10 times that of M82. Even within these classes it is a peculiar and interesting system. As was first shown by Gehrz, Sramek, & Weedman (1983), the infrared emission originates from at least three regions, whose relationship to the nuclei of the underlying galaxies IC 694 and NGC 3690 was elucidated by Telesco, Decher, & Gatley (1985). The nuclei, which are separated by about 20', were labeled “A” (IC 694) and “B” (NGC 3690) by Gehrz et al. Their third object, labeled “C”, lies approximately 7' to the north of B, within the disk of the galaxy NGC 3690. Subsequent work published in a conference proceedings by us (Eales et al. 1987) and independently by Fowler et al. (1987) showed that component B is itself double at 2.2 μm; the two components, which we have designated “B1” and “B2,” are separated by about 3'.

Since the work of Gehrz et al. (1983), Arp 299 has received much attention. Additional broad-band infrared studies have been made by Telesco et al. (1985), who mapped the system at 2.2 μm; Wright & McLean (1987), who presented a 2.5 pixel⁻¹ array image at 2.2 μm; Joy et al. (1989), who made 20–100 μm scans through the source; and Zhou et al. (1991) who have recently mapped the galaxies at 3.4 μm. Spectroscopy has been performed at 2–5 μm by Fischer et al. (1983), Beck, Turner, & Ho (1986), Depoy & Becklin (1991), and Nakagawa et al. (1989), and at optical and ultraviolet wavelengths by Augarde & Lequeux (1985), Friedman et al. (1987), and Armus, Heckman, & Miley (1990). Infrared polarimetry has been reported by Jones, Gehrz, & Smith (1990). Sargent & Scoville (1991) and Casoli et al. (1989) have mapped the system in the CO (J = 1–0) line, while Stanford & Wood (1989) and Baan & Haschick (1990) have studied the galaxies in the 21 cm H i line.

In this paper we present the full results of our 1.6–2.2 μm array observations on the University of Hawaii 2.2 m and the UKIRT telescopes. We couple these data with new 1.2–32 μm photometric and astrometric studies of the system made at the IRTF in order to study the infrared-emitting regions of these galaxies.

2. OBSERVATIONS

We used five different instruments on three telescopes to obtain our data. Three of the systems were array cameras; two were single-channel photometers. The systems are summarized in Table I and described in more detail below.

2.1. UKIRT Observations

The IRAC on UKIRT (McLean 1987) was used to obtain wide-field 2.2 μm images of the Arp 299 system with 0.6 pixel⁻¹ resolution in 1987 May. Figure 1 is a mosaic of six images made with this system. The observing procedure was to integrate for 120 s at the position of the object and to follow this by an integration of the same duration on a nearby area of blank sky. Pixels that were known to be faulty were ascribed intensity values equal to the median of the intensity values in the eight surrounding pixels. The remaining steps of the data reduction were to (1) subtract the bias and dark current from each frame, (2) divide the frames by flat fields obtained from the repeated observations of the sky, and (3) subtract the sky
frames from the object frames. Because of variable weather conditions, no flux calibration exists for the IRCAM data.

2.2. 2.2 Meter Infrared Observations

The Arp 299 system was observed with the JPL SISEX/SWIR 64 × 64 array (Capps et al. 1987) on the University of Hawaii 2.2 m telescope on the night of 1987 February 9 and on the nights of 1987 May 15, 16, and 17. The SISEX camera provided the highest resolution data as well as near-infrared color information on the nuclear regions of the galaxies. We observed components A and B at 1.65 μm (the H-band) and at 2.2 μm (the K-band); component C was observed only at 2.2 μm. The maps at 2.2 μm are shown in Figure 2. Data reduction was similar to that used at UKIRT except that flat fields were obtained by observations of the interior of the dome. The photometric calibration was made by observations of standard stars from the list of Elias et al. (1982). The flux densities in Table 2 were measured from the SISEX frames by adding up the flux within a chosen radius of the infrared peak and then making a correction for the residual background flux left after the sky subtraction. This correction was estimated by summing the flux in small regions around the edge of each frame that seemed clear of infrared emission from the object. As we could not tell whether any emission that was uniform over the array was genuine galaxy emission or the result of an inadequate sky subtraction, we set the radial profiles to zero at the edge of the array. The objects were detected with sufficiently high signal-to-noise ratio that the error is just the photometric error, which we estimate to be about 0.2 mag. The SISEX array has been shown to be linear down to a K magnitude of 16 mag arcsec−2 (Capps et al. 1987; Hodapp et al. 1987). The 4′1 flux densities in Table 2 for components A and C agree well with the 4′ IRTF photometry of Nakagawa et al. (1989). Because of its recently discovered double nature, no such comparison can be made for component B.

2.3. 2.2 Meter I-Band CCD Observations

An I-band image of the Arp 299 system (Fig. 3) was kindly obtained for us by Alex Storrs using the IFA/Galileo CCD camera (Hilvär, Henry, & Pilcher 1984). This camera uses a 512 × 512 pixel Texas Instruments chip, with a pixel size almost equal to that of the SISEX infrared array.

2.4. IRTF Observations

We observed Arp 299 with the IRFT bolometer BOLOI and the InSb detector RC2 using standard filters. The 1.25–3.8 μm observations with RC2, and a few of the 10.1 μm data, were obtained in 1986 February. The bulk of the 10.1–32 μm data were obtained in 1987 April. The weather during the 1986 observing run was good; the weather during the April run, which is when we did the 32 μm photometry, was exceptionally dry. The aperture was positioned by peak imaging at 2.2 μm for the near-infrared (1.25 < λ < 3.8 μm) observations and at 10.1 μm for the mid-infrared observations. Unfortunately, the 1987 data were plagued by a nonlinearity in the lock-in amplifier that was not discovered until several months later. We believe that

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![Figure 1](image.png)

**Figure 1.** Mosaic of six 2.2 μm images of Arp 299 obtained using the IRCAM system on UKIRT with 0.6 pixels. The contours are at evenly spaced increments of surface brightness. North is up; east is to the left.

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**TABLE 1**

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Instrument</th>
<th>Number of Pixels</th>
<th>Pixel Size</th>
<th>Field of View</th>
<th>Wavelength (μm)</th>
<th>Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKIRT</td>
<td>IRCAM</td>
<td>58 × 62</td>
<td>0.6</td>
<td>36′ × 39′</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>UH 2.2 m</td>
<td>SISEX</td>
<td>64 × 64</td>
<td>0.145</td>
<td>9.3 × 9.3</td>
<td>1.65–2.2</td>
<td>2, 4</td>
</tr>
<tr>
<td>UH 2.2 m</td>
<td>TI CCD</td>
<td>512 × 512</td>
<td>0.14</td>
<td>70 × 70</td>
<td>0.8</td>
<td>3</td>
</tr>
<tr>
<td>IRTF</td>
<td>BOLOI, RC2</td>
<td>1</td>
<td>1.8–7.2</td>
<td>...</td>
<td>1.25–32</td>
<td>5</td>
</tr>
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</table>

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**TABLE 2**

<table>
<thead>
<tr>
<th>Component</th>
<th>Aperture Diameter</th>
<th>H Band (1.65 μm) (mJy)</th>
<th>K band (2.2 μm) (mJy)</th>
<th>H − K (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.7</td>
<td>9.1</td>
<td>11.2</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>15.5</td>
<td>18.4</td>
<td>0.67</td>
</tr>
<tr>
<td>B1</td>
<td>1.7</td>
<td>9.2</td>
<td>19.8</td>
<td>1.31</td>
</tr>
<tr>
<td>B2</td>
<td>1.7</td>
<td>10.1</td>
<td>10.7</td>
<td>0.54</td>
</tr>
<tr>
<td>C</td>
<td>1.7</td>
<td>...</td>
<td>9.5</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>...</td>
<td>11.1</td>
<td>1.11</td>
</tr>
</tbody>
</table>

*a Photometric errors are approximately 20% (1 σ), including calibration.

*b H − K color for component C is taken from Nakagawa et al. 1989 using a 4′ diameter aperture.

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subsequent recalibration has allowed us to remove this error to about the 10% level. Because the 32 μm filter is known to have a small blue leak whose relative contribution varies with atmospheric transparency, calibration at this wavelength was checked each night by comparing the measured 32 μm flux densities of the asteroids Ceres, Cybele, Eunomia, and Pallas with estimates based on blackbody extrapolation of their 10, 20, and 25 μm flux densities. No anomalies in the asteroids' 32 μm flux densities were found, indicating that on the nights in question the atmospheric transparency was high enough for the blue leak to be negligible.

Multiaperture photometry at 10.1 μm was obtained for the A and B1 components, in order to investigate the spatial distribution of the mid-infrared emission. A separate 10.1 μm measurement was made at the position of the optical nucleus of NGC 3690. Measurements were made through focal plane apertures of diameter 1, 1.5, 2, 3, and 4 mm for the B1 component and through the four larger apertures for the A component. In this paper we have assumed a scale of 1.9 mm−1 for the IRTF measurements; the actual beam sizes depend slightly on seeing and instrumental factors.

3. ASTROMETRY AND IDENTIFICATIONS

Astrometric positions for the 10.1 μm sources associated with A, B, and C are given in Table 3. The positions were determined with respect to two AGK 3 stars whose positions, corrected for proper motion but not precession, are also given in Table 3. It may be seen that in each case there is positional agreement to within 1″ between the 10.1 μm and the radio positions. The positions of the visible peaks of the two galaxy nuclei agree poorly with those of the infrared and radio sources, however. In the case of IC 694 (Source A) the visible

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peak is poorly defined, but in the case of source B (NGC 3690) the displacement of the 10.1 μm source from the visible peak is unambiguous, with the 10.1 μm infrared peak situated about 3° southeast of the visible nucleus. The displacement of 10.1 μm and visible peaks was directly measurable at the telescope.

The interpretation of the double 2.2 μm source associated with NGC 3690 (source B) is now clear. Source B2, which dominates the I-band image, is the optical nucleus, while source B1, 3° to the southeast, is the location of the main 10.1 μm and radio sources. These identifications are supported by (1) the fact that the displacement between the visible and 10.1 μm sources agrees with the displacement between B1 and B2, (2) the fact that the displacement between C and B1 in the UKIRT image (Fig. 1) agrees with the separation of sources B and C at 10.1 μm and at radio wavelengths, and (3) the fact that B1 is much redder at $H - K$ than B2 (see Table 2).

4. SOURCE SIZES AND STRUCTURES

4.1. 1.6–2.2 Micron Array Images

The images taken with the SISEX array (Fig. 2) have the highest spatial resolution (1′0 HPBW) of any infrared data on this object. To obtain an estimate of the point-spread functions for the SISEX observations of components A and B, an SAO star was observed immediately before or after each galaxy observation. The star chosen was close to the galaxy, in order that conditions for the galaxy and star observation be as similar as possible. The integration time for the star observations was at least half that for the galaxy observations, so that the degradation in spatial resolution produced by the buildup of tracking errors would be similar. We did not follow the same careful procedure for the C component, but by chance we did observe a star at about the same time as the galaxy observation, which we believe gives an adequate representation of the point-spread function. Figure 4 shows azimuthally summed radial intensity profiles for the four components, together with the azimuthally summed profile of the appropriate nearby SAO star. Component A is clearly extended with a FWHM of about 2″ (400 pc). The cores of components B1, B2, and C are indistinguishable from stars, implying that they have diameters of less than about 1″ (200 pc) at 2.2 μm. The fact that A is extended and C is compact at 2.2 μm is also indicated by the differences between the 1.7 and 4.1 flux densities in Table 2.

4.2. Multiaperture Photometry

Structural information at longer wavelengths can be obtained from the multiaperture photometry. Table 4 contains the photometric measurements of components A and B between 1.25 and 10.1 μm at a variety of apertures. In the case of component B, the fluxes refer primarily to component B1 since B1 is stronger than B2 at both 2.2 μm and 10.1 μm—the wavelengths used to determine the peak for photometric purposes. Our most extensive data are at 10.1 μm; they are plotted in Figure 5. They indicate that both A and B are most probably extended; in each case about 20% of the 10.1 μm flux density comes from outside of a region 3″ in diameter. Within the precision of the measurements, however, we cannot with certainty exclude the possibility that all of the 10.1 μm flux density comes from within 3″. The steep rise in the flux density of B between 1.9 and 2.8 suggests that component B1 has a diameter on the order of 2″ (400 pc) at 10.1 μm, the contribution of B2 to the flux densities measured for B1 is negligible; a direct measurement with a 3″ aperture centered precisely on the optical nucleus of NGC 3690 yielded only 33 ± 12 mJy—less than 5% of the flux density measured for B1 with a similar aperture.

Our data at 1.2–2.2 μm corroborate the more extensive results of Nakagawa et al. (1989) in showing that both A and B are extended in this wavelength range. The ratio of flux densities in the 3.8 and 7.6 diaphragms is slightly smaller at 1.2–2.2 μm than at 10 μm for both galaxies, indicating that the 10 μm emission is more confined than the near-infrared emis-
sion. Our 3.8 μm data do not follow this trend, and a straightforward interpretation of the data in Table 4 would be that both A and B are more compact at 3.8 μm that at either longer or shorter wavelengths. Although plausible physical models could be constructed to explain such a phenomenon, we are reluctant to press them without further observational confirmation. Zhou, Wynn-Williams, & Sanders (1991) did not see any significant difference between their 2.2 and 3.4 μm diameters of components A and B taken at UKIRT.

4.3. Comparison of IRAS and IRTF Flux Densities

A third method of obtaining some structural information on the source can be obtained by comparing the IRAS fluxes at 12 and 25 μm with the sum of the IRTF fluxes at these wavelengths. The 10.1–32 μm flux densities of components A, B, and C, as measured through a 5.7 diaphragm on the IRTF, are listed in Table 5. Our 12.5 μm flux densities for components A and B agree satisfactorily with those of Gehrz et al. (1983), but our 20 μm flux densities are about a factor of 2 higher than theirs. Our 20 μm flux densities for A and B (but not C) are also higher than those of Teleco et al. (1985), although their beam size was smaller than ours. Our data were taken under excellent conditions and show good agreement between observations obtained on different nights. We do not know the cause of the discrepancy, but we note that the 20 μm window is very wide, with weather-dependent transmission. The effective

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**TABLE 5**

10–32 Micron Flux Densities in Arp 299

<table>
<thead>
<tr>
<th>WAVELENGTH (μm)</th>
<th>FLUX DENSITY (Jy)*</th>
<th>IRAS/IRAS RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>0.54</td>
<td>0.33</td>
</tr>
<tr>
<td>12.5</td>
<td>1.11</td>
<td>1.7</td>
</tr>
<tr>
<td>20</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td>25</td>
<td>12.4</td>
<td>6.9</td>
</tr>
<tr>
<td>32</td>
<td>27 ± 8</td>
<td>13 ± 4</td>
</tr>
</tbody>
</table>

* Errors in IRTF measurements (1 σ including calibration) are approximately 10% for 10–12.5 μm, 20% for 20–25 μm data, and as shown for 32 μm data.

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the total flux density of \((A + B + C)\) in 6\(^\circ\) apertures from Table 1 of Nakagawa et al. (1989) with the integrated 2.2 \(\mu\)m flux density of 229 mJy estimated by Telesco et al. (1985). Since the large-scale 2.2 \(\mu\)m emission from Arp 299 has the color of ordinary starlight (Telesco et al. 1985), we may deduce that the 12–25 \(\mu\)m emission regions in Arp 299 are more compact than the general distribution of stars. It is probable, though not proven, that the 60–100 \(\mu\)m emission is similarly more concentrated than the stars.

From our ground-based observations alone we may conclude the following about the sizes of the individual sources in Arp 299.

**Source A.**—This source, the source at the center of IC 694, is the most luminous of the infrared sources in Arp 299 (Joy et al. 1989). Almost all indications are that the source is extended at infrared wavelengths. The 2.2 \(\mu\)m images in Figure 2 show a resolved 400 pc (2\(^\circ\)) core, while the multiple-aperture photometry at JHK and 10 \(\mu\)m (Table 4, Fig. 5, and Nakagawa et al. 1989) indicate that the source extends beyond 1 kpc diameter. The only conflicting evidence is at 3.8 \(\mu\)m; as we discussed in § 4.2, we would like to see the 3.8 \(\mu\)m measurements repeated. A scale size of 1 kpc is comparable to that deduced for larger samples of \textit{IRAS} galaxies at 10 \(\mu\)m (Hill, Becklin, & Wynn-Williams 1988) and at 6 cm (Eales, Wynn-Williams, & Beichman 1988) and is compatible with the assumption that the main source of power in this galaxy is star formation rather than an active nucleus. The latter scenario was suggested by Nakagawa et al. (1989) on the basis of the JHK colors and the presence of a compact nuclear radio source in IC 694. Our 2.2 \(\mu\)m observations failed to find any evidence for an unresolved core. Nor did we find any significant change of \(H-K\) color with aperture size either within our SISEX measurements themselves (Table 2) or when our data were compared with the larger scale measurements of Nakagawa et al. (1989).

**Source B.**—Both of the sources near the center of NGC 3690 have diameters of less than 1\(^\circ\) (200 pc) at 2.2 \(\mu\)m. There is some evidence in Figure 5 that B1—the source that displays the strongest radio and far-infrared emission—is extended on a scale of 1 kpc at 10 \(\mu\)m. We will discuss the identifications of B1 and B2 in § 5.2.

**Source C.**—This source is unresolved (\(\leq 1\)\(^\circ\)) by our 2.2 \(\mu\)m array measurements. The multiperture photometry of Nakagawa et al. (1989) indicates that the source is extended at 2.2 \(\mu\)m on a scale of 4\(^\circ\)–10\(^\circ\), but this result is not surprising given the location of source C within the luminous boundaries of NGC 3690. There is no direct evidence concerning the size of C at 10 \(\mu\)m or longer.

Taken together, our infrared observations imply that the main sources of luminosity in the Arp 299 system are strongly concentrated into a small number of compact regions. Infrared observations provide a quite different impression from those at visible wavelengths; both Friedman et al. (1987) and Armus et al. (1990) stress that Hz emission is detected over wide areas of the galaxies. The most likely explanation for the difference is that the main luminosity sources in Arp 299 are associated with substantial amounts of extinction that attenuate the Hz emission from these regions.

5.2. Where Is the Nucleus of NGC 3690?

It is by no means obvious whether B1 or B2 marks the dynamical center of NGC 3690, and it is possible that neither does. Visible-wavelength data on the rotation curve (Augarde & Lequeux 1985) have insufficient spatial resolution to

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**5. DISCUSSION**

5.1 The Sizes of the Emitting Regions

Our observations have yielded information about the morphology of the infrared emission from Arp 299 on several spatial scales. Dealing with the large-scale structure first, we have shown that at least 75% of the total mid-infrared emission (12–25 \(\mu\)m) comes from within 550 pc (2\(^\circ\) radius) of the positions of A, B1, and C (see § 4.3). The equivalent ratio at 2.2 \(\mu\)m is 33%. The latter percentage was obtained by comparing...
separate the two sources. The infrared properties of B1 and B2 can be interpreted in more than one way: on one hand, it could be argued that B1 is the nucleus because it has a much higher thermal infrared and radio luminosity than B2; on the other hand, it could be argued that B2 is the nucleus because its $H-K$ color is closer to that of a normal galaxy stellar population—namely around 0.25 (Aaronson 1978). Either alternative leaves us with the problem of explaining what the nonnuclear source is. In the first case our problem is that we have a major concentration of relatively normally colored stars (B2) situated 600 pc away from a nucleus that is highly obscured at visible wavelengths. In the second case we have a powerful infrared and radio source (B1) situated 600 pc away from a relatively normal galaxy nucleus. In the latter scenario, sources B1 and C are somewhat equivalent to each other in the sense that they are regions of infrared and radio activity on opposite sides of a comparatively quiescent nucleus.

5.3. The Nature of Object C

As we have mentioned before, the most remarkable feature of the Arp 299 system is the fact that it contains more than two centers of major activity. Most other powerful infrared galaxies have only one or two peaks of emission, as would be expected if their high luminosities are triggered by the merger of a pair of galaxies. Broadly speaking, two kinds of explanation have been put forward for the extra sources in Arp 299, namely that they mark the nuclei of additional interacting galaxies, (e.g., Casoli et al. 1989) or that they are regions of intense star formation in the disk of NGC 3690 or at the interface between the two galaxies NGC 3690 and IC 694 (e.g., Sargent & Scoville 1991).

In this section we will focus our attention on object C, but much of the ensuing discussion can equally well be applied to sources B1 and C'. Arguments in favor of the hypothesis that C is a galaxy nucleus include the following:

1. Major bursts of star formation are most likely to occur at a point to which interstellar matter is gravitationally attracted; most starbursts are observed to occur in the potential well surrounding a galaxy nucleus.

2. Every other known astronomical object that has a bolometric luminosity as high as that of object C either coincides with or immediately surrounds the nucleus of a galaxy. We base this statement on an assumed bolometric luminosity for object C of $4.8 \times 10^{10} L_\odot$, a value which is obtained by multiplying the total luminosity of Arp 299 (Soifer et al. 1987) by the fraction of the total 25 $\mu$m flux density of Arp 299 that is contributed by object C (Table 5). To put this luminosity in perspective, we note that object C is 37 times more luminous than the giant H II complex NGC 5461 in M101, 1200 times more luminous than 30 Doradus in the Large Magellanic Cloud, and 6000 times more luminous than W51 in our Galaxy (Wynn-Williams & Becklin 1986). It is also 5 times more luminous than any of the nonnuclear sources in the infrared galaxy NGC 3310 (Telesco & Gatley 1984). Perhaps most remarkably, it exceeds by a factor of 3 the total infrared emission by dust from the whole of the Milky Way (Cox, Krügel, & Mezger, 1986).

3. Object C is remarkably compact, given its high luminosity. Although there is no direct size measurement at 60 $\mu$m, it is not unreasonable to assume that a substantial fraction of the $4.8 \times 10^{10} L_\odot$ output from object C is generated from a region smaller than 200 pc across—the upper limit to the 2.2 $\mu$m diameter. Object C is therefore considerably smaller than the giant H II regions in the spiral arms of M33 and M101, (e.g., Shields 1990). It is also much smaller than the infrared-emitting region of M82 (e.g., Telesco 1988), which has a total luminosity slightly less than that of object C, and is at least 500 pc in diameter; if object C is a starburst, then the star formation rate per unit volume is at least 10 times as intense as that in M82! The small size of object C implies some remarkable physical conditions in its interstellar medium as well. Sargent & Scoville (1991) estimate an H$_2$ mass of 2.1 x $10^9$ from three compact sources near C-C'. If we were to squeeze one-third of this mass into a 200 pc sphere, it would have a mean density of 6000 atoms cm$^{-3}$, more than 1000 times greater than the typical interstellar density in the Galactic plane of the Milky Way.

4. The 2.2 $\mu$m surface brightness of C is at least as high as that of the centers of most normal galaxies. The most useful data for this comparison are the K magnitudes of Virgo Cluster galaxies published by Devereux, Becklin, & Scoville (1987). These were obtained with a 5.5' diaphragm. If we correct the data in Table 2 for the difference in distance between Arp 299 (42 Mpc) and the Virgo Cluster (16.9 Mpc), we can estimate that component C would have a K magnitude of 10.1 in a 4.3 beam if we were moved to the distance of the Virgo Cluster. As may be seen from the histogram published by Eales et al. (1990), this surface brightness is close to the upper limit of what is found in the central regions of normal galaxies.

On the other hand, there are some arguments against the hypothesis that C is another nucleus. They include the following:

1. K-band spectroscopy by Ridgway, Wynn-Williams, & Becklin (1991) shows no signs of the 2.3 $\mu$m CO absorption feature in source C. Little of the 2.3 $\mu$m emission therefore comes from a normal population of evolved stars.

2. Sargent & Scoville (1991) argue that the velocity dispersion of the 2.6 mm CO emission is less than would be expected for a galaxy nucleus.

3. A simultaneous collision between more than two galaxies has a low statistical probability. This argument becomes particularly troublesome with the need to account for sources B1 and C' as well as source C.

Overall, we are ambivalent on the question of whether or not object C (and by extension C' and perhaps B1) are associated with individual galaxies. Gaskell (1985), however, has pointed out that many disk galaxies are accompanied by several dwarf companions, to which they are gravitationally bound. The Milky Way has the Magellanic Clouds, while M31 has NGC 205 and NGC 221. A collision between such a multiple system and another major galaxy might well lead to multiple centers of activity, as each of the dwarfs from the first galaxy triggers a burst of star-forming activity as it collides with the gas-rich disk of the second major galaxy. In this scenario, components C, C', and possibly B1 might be starbursts or some kind of nonstellar phenomenon triggered by the passage of dwarf companions of IC 694 colliding with the disk of NGC 3690. If object C contained a dwarf galaxy, its low CO velocity dispersion could have a fairly natural explanation.

6. CONCLUSIONS

New imaging at 1.65-2.2 $\mu$m coupled with photometry and astrometry at longer wavelengths has allowed us to draw the following conclusions about the nature of the infrared emission from the interacting system Arp 299.
1. Of the two sources that lie close to the center of NGC 3690, the redder one, component B1, coincides with the position of the peaks of 10.1 $\mu$m and 6 cm emission. Component B2, which is 3" (600 pc) northwest of B1, coincides with the optical nucleus of the galaxy. It is not certain whether B1 or B2 corresponds to the dynamical nucleus of the galaxy.

2. Approximately 75% of the 12–25 $\mu$m power from Arp 299 comes from three regions, each smaller than 600 pc in diameter and centered on components A, B1, and C. The distribution of mid-infrared emission is more concentrated than the emission from starlight.

3. The 2.2 $\mu$m emission from IC 694 (component A) is extended on a scale of 400 pc. We do not detect any signs of a compact AGN at this wavelength.

4. We are still unsure as to whether or not source C marks the position of a third galaxy nucleus. It is more luminous than any known nonnuclear astronomical object and has physical conditions even more extreme than those in well-established starburst nuclei. The main arguments against its being a nucleus are based on the implausibility of multiple simultaneous mergers.

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REFERENCES

Gaskell, C. M. 1985, Nature, 315, 386
McLean, I. S. 1987, in Infrared Astronomy with Arrays, ed. C. G. Wynn-Williams & E. E. Becklin (Honolulu: Univ. of Hawaii), 180
Telesco, C. M. 1988, ARA&A, 26, 343

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