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# $10^{12}$ $L_\odot$ STARBURSTS AND SHOCKED MOLECULAR HYDROGEN IN THE COLLIDING GALAXIES ARP 220 (= IC 4553) AND NGC 6240[1]

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## ABSTRACT

We present infrared spectroscopy and photometry and optical spectroscopy of the exceedingly luminous interacting galaxies Arp 220 (= IC 4553) and NGC 6240. These galaxies are the sites of exceedingly powerful bursts of star formation, as shown by (1) the luminosity and extent of the stellar component seen near 2 $\mu$m; (2) the large population of red supergiants required to account for the depth of the stellar CO absorption; (3) the absorption and emission features in the spectrum longward of 3 $\mu$m; and (4) the extended luminosity source indicated by the spatial extent of the galaxies at 10 $\mu$m. Scaled-up models similar to those developed for less luminous starburst galaxies are consistent with this hypothesis. Arp 220 also appears to have an active nucleus, possibly of Seyfert type 2. Both galaxies also show strong lines from shocked molecular hydrogen, which may arise in the collisions of their interstellar clouds in an ongoing interaction.
*Subject headings:* galaxies: individual — galaxies: photometry — interstellar: molecules — stars: formation

## I. INTRODUCTION

Intense and short-lived bursts of star formation can dominate the observable properties of certain galaxies with powerful far-infrared excesses. Rieke and Low (1975) suggested such an explanation for the infrared luminosity of NGC 253, while Harwit and Pacini (1975) and Kronberg, Biermann, and Schwab (1981) pointed out the potential correlation between large populations of massive stars and strong nonthermal radio fluxes generated by supernova remnants. Larson and Tinsley (1978) compared the *UBV* colors of normal and interacting galaxy samples and concluded that tidal interactions induce elevated rates of star formation. Rieke *et al.* (1980) modeled the radio, infrared, ionizing flux, and X-ray properties of M82 and NGC 253, showing that the starburst hypothesis accounted for the properties of these galaxies in a consistent manner. Using less detailed arguments, they suggested that the same process could account for the properties of a large percentage of galaxies with strong infrared excesses. Weedman *et al.* (1981) and Gehrz, Sramek, and Weedman (1983) have applied similar arguments to NGC 7714 and NGC 3690.

Most of the starbursts studied to date are strongly concentrated in the central few hundred parsecs of the galaxy, even though the luminosity can be as large as that from the entire remaining galaxy. Consequently, the star formation rate and energy density in this central region must be thousands of times higher than is typical in other galactic nuclei or away from the nuclei in the starburst galaxies. Under these conditions, the process of star formation itself appears to be altered as shown by an initial mass function (IMF) biased strongly toward massive stars compared with the IMF in the solar neighborhood (Rieke *et al.* 1980).

There is no clear understanding of how starbursts are triggered or of the origin of the interstellar material which they consume, nor is it clear how long they last, how they die out, or what they evolve into. It has been suggested that they are terminated when the energy released in supernova explosions is sufficient to eject the remaining interstellar material from the galactic nucleus (Loose, Krugel, and Tutukov 1982), and it does appear that the interstellar material is being ejected by such a process in M82 (Rieke *et al.* 1980; Biermann 1984).

Possible answers to some of these questions can be constrained by determining whether there is an upper limit to the luminosity and energy density in a starburst and studying the properties of the most powerful starbursts. Two galaxies with exceptionally large far-infrared luminosities have been identified from the *Infrared Astronomical Satellite* (*IRAS*) survey, Arp 220 (Soifer *et al.* 1984) and NGC 6240 (*IRAS Circ.*, No. 4, 1983). These galaxies have been studied previously without the achieving of a consensus on the nature of their activity (e.g., Fosbury and Wall 1979; Heckman *et al.* 1983*a*, *b*; Fried and Schulz 1983; Baan and Haschick 1984; Wright, Joseph, and Meikle 1984). We report detailed observations which show that they are sites of immense starbursts, involving nearly $10^{10}$ $M_\odot$ of newly formed stars. Models constructed along the lines of those of Rieke *et al.* (1980) are consistent with the starburst hypothesis and help in the understanding of conditions in their nuclei. Injecting adequate matter to fuel such powerful starbursts is a difficult problem unless a galaxy undergoes a strong outside perturbation; it is probably not coincidental that these galaxies and others with very strong starbursts appear to be undergoing interactions or to be morphologically disturbed. Both galaxies have strong lines from shocked molecular hydrogen gas; we find that these lines are probably not associated directly with the starbursts but may arise from the process of galaxy collision itself. After the starburst has died out, these galactic nuclei will contain some $10^9$ $M_\odot$ of massive stellar remnants; Weedman's (1983) suggestion of possible subsequent evolution into a classical "active" galaxy needs more detailed consideration.

[1] Observations reported here used the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona; the Infrared Telescope Facility, operated by the University of Hawaii under contract from NASA, and the Canada-France-Hawaii Telescope, operated by NRC Canada, CNRS, and the University of Hawaii.

TABLE 1

TEN AND TWENTY MICRON PHOTOMETRY

| Galaxy | Aperture (arcsec) | Position[a] | N (mJy) | Q (mJy) |
|---|---|---|---|---|
| Arp 220 .......... | 5.8 | 0 | 198 ± 10 | ... |
| | | 3 E | 62 ± 34 | ... |
| | | 3 W | 143 ± 22 | ... |
| | | 3 N | 134 ± 24 | ... |
| | | 3 S | 91 ± 11 | ... |
| | | 3 NW | 213 ± 11 | 2560 ± 200 |
| | | 5 NW | 171 ± 19 | ... |
| | | 7.5 NW | 139 ± 20 | ... |
| | | 10 NW | 121 ± 17 | ... |
| NGC 6240 ....... | 5.8 | 0 | 252 ± 10 | ... |
| | 4.0[b] | 0 | 120 ± 15 | 1090 ± 130 |

[a] Displacement (arcsec) from the radio peak position.
[b] From Wright, Joseph, and Meikle (1984).

## II. NEW OBSERVATIONS

### a) *Infrared Photometry*

Photometry at 10 and 20 μm was conducted with the Infrared Telescope Facility (IRTF) and its facility bolometer photometer. Measurements were made through a 5″.8 diameter beam with reference areas 10″ to the north and south of the galaxy nucleus. Calibration was as described in Rieke, Lebofsky, and Low (1984). The results are summarized in Table 1, which also includes photometry of NGC 6240 by Wright, Joseph, and Meikle (1984). Note that 10 μm flux from Arp 220 is detected well to the northwest of the position of peak radio surface brightness, with the maximum infrared surface brightness possibly also offset slightly in this direction. Our measurement at 20 μm was centered on the point of maximum brightness at 10 μm. NGC 6240 shows a large dependence of flux on aperture at 10 μm. Thus both sources are extended at this wavelength. In addition to the broad-band photometry in Table 1, we observed each galaxy through a narrow-band filter centered at 10.3 μm. Relative to a featureless Rayleigh-Jeans spectrum (α Boo), we found that the ratio of fluxes detected in the narrow to the broad *N* filter were 0.14 ± 0.12 for Arp 220 and 0.30 ± 0.16 for NGC 6240.

The ratios of fluxes detected in the narrow-band filter at 10 μm to those detected in the full *N* filter (bandwidth 5 μm) imply strong silicate absorption features. We have estimated the strength of this feature by convolving its shape as determined in Galactic sources with the filter functions. We estimate an optical depth at the minimum of the feature of $\sim 1.8$ for NGC 6240 and $\geq 2$ for Arp 220. These depths may be overestimated by $\sim 0.2$ because of emission features at 8.7 and 11.3 μm, whose presence is implied by our detection of an accompanying feature at 3.27 μm (see Fig. 1).

Near-infrared photometry was conducted with the Multiple Mirror Telescope and with the Steward Observatory 2.29 m telescope. The procedures with the MMT are described in § II*b*. With the 2.29 m, observations were made with a photometer equipped with a helium-cooled InSb detector, with reference areas 18″ to the north and south of the galaxy nucleus, and through apertures of 7″.8 and 3″.9 diameter. At the time, the seeing was 1″–1″.5. Calibration was as described in Campins, Rieke, and Lebofsky (1984). The results, shown in Table 2, demonstrate that a significant portion of the flux from both galaxies at 2 μm is generated in an extended source.

TABLE 2

MULTIAPERTURE PHOTOMETRY

| Galaxy | Filter | Aperture 3″.9 | 7″.8 | 8″.7 |
|---|---|---|---|---|
| Arp 220 .......... | *J* | 6.6[a] | 11.4 | 14.4 |
| | *H* | 13.0 | 21.5 | 27.0 |
| | *K* | 18.3 | 24.1 | 30.9 |
| NGC 6240 ....... | *J* | 17.8 | 25.7 | 28.2 |
| | *H* | 34.3 | 44.8 | 49.2 |
| | *K* | 40.4 | 51.8 | 57.3 |

[a] Fluxes in mJy; relative errors ±2%.

### b) *Infrared Spectroscopy*

Infrared spectrophotometry between 2 and 2.5 μm was obtained with the Multiple Mirror Telescope and its facility infrared photometer, which is equipped with a circularly variable filter of resolution 1.1%. Most of the spectra were taken through an aperture of 8″.7 diameter and with reference beams spaced 15″ on either side of the galactic nucleus in elevation. The photometer uses an InSb photovoltaic detector cooled to 4 K with liquid helium. The spectra are presented in Figure 1. The signal-to-noise ratio in these observations is built up by a relatively large number of automated scans over the spectrum, so that potential errors due to changes in transparency or irregularities in tracking are minimized. In addition, with this technique the observational errors can be determined accurately from the repeatability of the scans. The signal-to-noise ratio for NGC 6240 exceeds 100, while for Arp 220 it exceeds 60. Atmospheric absorptions were removed from the galaxy spectra by comparing them with spectra of solar-type stars close on the sky to the galaxies. The overall calibration of the spectrophotometry was as discussed by Campins, Rieke, and Lebofsky (1984).

From 3.2 to 3.6 μm, spectra of these galaxies were obtained

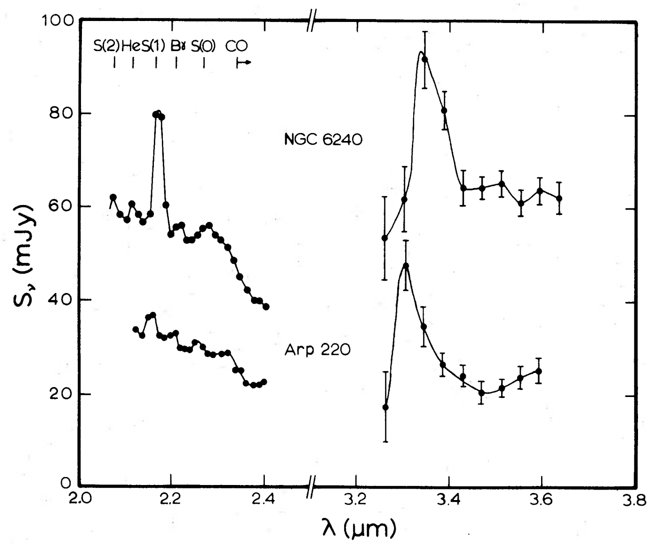


FIG. 1.—The near-infrared spectra of NGC 6240 and Arp 220. The errors for the 2.0–2.4 μm region are approximately the size of the symbol for NGC 6240, and approximately twice the size of the symbol for Arp 220. The lines of $H_2$ (2.035, 2.123, and 2.223 μm rest wavelengths), He I (2.05 μm), Brγ (2.166 μm), and the CO bandhead (2.3 μm) are indicated.

with the Canada-France-Hawaii Telescope, using its facility infrared photometer with a solid nitrogen–cooled InSb detector and a circularly variable filter with a resolution of 3%. The focal-plane aperture was 8″.0 in diameter, and sky reference areas were placed 15″ to the north and south of the galaxy nucleus. The resultant spectra are shown in Figure 1.

The most spectacular result of the spectrophotometry is the extremely strong molecular hydrogen emission from both galaxies (molecular hydrogen had been detected from NGC 6240 by Becklin, DePoy, and Wynn-Williams (1984), although we were unaware of it at the time of our observations). We also detect Br$\gamma$ emission in both cases, and for NGC 6240, He I. Our spectrum does not extend to short enough wavelengths to detect He I in Arp 220. Some of our observations of NGC 6240 were obtained with a beam only 5″.3 in diameter to help localize the molecular hydrogen emission; we found that the molecular hydrogen is at least as centrally concentrated as the general 2 $\mu$m flux. The spectrophotometry also shows strong emission features at 3.27 $\mu$m from both galaxies; the species giving rise to these features is as yet not known. In addition, both galaxies have broad spectral absorptions longward of 2.3 $\mu$m due to CO.

### c) *Optical Spectroscopy*

We obtained optical spectra of Arp 220 and NGC 6240 with the photon counting intensified Reticon spectrograph on the Steward Observatory 2.29 m telescope. The spectra were taken through a 2″.5 aperture under photometric conditions. The grating had 600 lines mm$^{-1}$, giving an instrumental line width of 7 Å FWHM; a spectral range from 3700 to 6800 Å was recorded. Standard stars from Stone (1977) were observed to provide a relative flux calibration; the absolute calibration was set by comparison with the line strength quoted for H$\beta$ in NGC 6240 by Fosbury and Wall (1979).

For NGC 6240 we find a redshift of $z = 0.02372 \pm 0.0003$, which is compatible with the values obtained by Fosbury and Wall (1979) and Fried and Schulz (1983). We find no evidence for a difference in velocity between absorption and emission as reported by Fosbury and Wall (1979). Both the permitted and the forbidden lines have symmetrical profiles with similar widths of $640 \pm 90$ km s$^{-1}$ FWHM (after correcting for the instrumental resolution). NGC 6240 is characterized by strong emission lines of low-ionization species such as [O II] $\lambda$3727, [O I] $\lambda$6300, [N II] $\lambda$6584. The observed line ratios are $\lambda3727/\lambda5007 \sim 1.5$, $\lambda6300/\lambda5007 \sim 2.2$, $\lambda5007/\lambda4861 \sim 1.4$, and $\lambda6584/\lambda6563 \sim 0.9$.

For Arp 220 we find a redshift of $z = 0.01847 \pm 0.0003$. The oxygen line at 5007 Å has a width of $300 \pm 70$ km s$^{-1}$ FWHM (after correction for instrumental resolution). The line profile is asymmetric, with a strong blue wing. This type of line profile is common in Seyfert galaxies and is attributed to outflow of the line emitting gas from the nucleus of the galaxy (Heckman *et al.* 1981). Arp 220 has strong high-excitation lines such as [O III] $\lambda$5007. The observed line ratios are $\lambda3727/\lambda5007 \sim 0.22$, $\lambda6300/\lambda5007 \leq 0.2$ ([O I] $\lambda$6300 is not detected in our spectrum), and $\lambda6584/\lambda6563 \sim 1.3$. H$\beta$, H$\gamma$, and H$\delta$ are all in absorption, presumably because of the presence of a large number of hot stars. The maximum plausible equivalent width of H$\beta$ absorption in such a population of stars is $\sim$7 Å (Strömgren 1963); the observed equivalent width of about 4 Å leads to an upper limit of 3 Å for the equivalent width of any H$\beta$ emission. We therefore obtain $\lambda5007/\lambda4861 \geq 4$.

## III. DISCUSSION

### a) *Luminosities*

Both Arp 220 and NGC 6240 are of exceptionally high luminosity, most of which emerges in the far-infrared as shown by the measurements by *IRAS*. We have estimated the distances of these galaxies from their redshifts of 5420 km s$^{-1}$ (Mirabel 1982) and 7362 km s$^{-1}$ (Fosbury and Wall 1979), respectively, and an assumed Hubble constant of 80 km s$^{-1}$ Mpc$^{-1}$. Their luminosities are then $1 \times 10^{12}$ $L_\odot$ and $0.5 \times 10^{12}$ $L_\odot$, as indicated in Table 3. These luminosities place them among the most energetic galaxies known, nearly comparable with Markarian 231.

The *IRAS* flux measurements refer to beams of approximately 1′ diameter and therefore include virtually the entire galaxy. Soifer *et al.* (1984) deconvolved the *IRAS* scans of Arp 220 with the point-spread function of the instrument to show that the emitting region is smaller than 25″ in diameter. Our photometry in Table 1 can localize the emitting region further.

Since both galaxies have strong silicate absorption, to compare our $N$ photometry with the *IRAS* measurements at 12 $\mu$m, we must correct for the shape of the spectrum. To do so, we have assumed a silicate feature with optical depth $\tau = 2.0$ for both galaxies and an overall spectral slope fitted to our measurements at $N$ (10.6 $\mu$m) and $Q$ (21 $\mu$m) for Arp 220 and to the *IRAS* measurements for NGC 6240. We have convolved the resulting spectrum with the filter functions for the $N$ band and the *IRAS* band 1 (12 $\mu$m). We find that the ground-based photometry corresponds to a flux at 12 $\mu$m in a 5″.8 beam of 320 mJy for Arp 220, or 67% of the *IRAS* flux. For NGC 6240 the flux in a 5″.8 beam is 330 mJy, or 65% of the *IRAS* flux measurement. For Arp 220 a similar comparison between the 21 $\mu$m ground-based flux measurement and the *IRAS* observation at 25 $\mu$m shows that about 65% of the flux is within the 5″.8 beam used from the ground. For both galaxies, we conclude that most but not all of the infrared flux lies within our 5″.8 beam. The detailed mapping around the nucleus of Arp 220 at 10 $\mu$m (see Table 1) demonstrates that most of the flux missing from the single 5″.8 beam lies just outside it. At the distances of these galaxies, 5″.8 corresponds to about 2 kpc.

The luminosities of these galaxies in the near infrared are also phenomenal. Within an 8″.7 beam, corresponding to about 3 kpc, the $K$-magnitude of Arp 220 is equivalent to an absolute magnitude of $M_K = -23.3$; the corresponding magnitude for NGC 6240 is $M_K = -24.6$ within the 4 kpc region subtended by 8″.7. As discussed in § IIIc, the nuclei are heavily obscured by dust within the galaxies; after correction for reddening, we find the absolute magnitudes to be $M_K \approx -24.5$ for Arp 220 and $-26$ for NGC 6240. As shown in Figure 1, both galaxies show strong absorption bands of CO, indicating that the 2 $\mu$m fluxes are dominated by the output of red giant or supergiant stars. In order to account for the observed absorption at 2.3–2.4 $\mu$m in NGC 6240 by interstellar CO, a mean column density of $N(\mathrm{CO}) > 3 \times 10^{20}$ cm$^{-2}$ ($A_v > 3000$ mag) would be required, assuming a Doppler parameter $b = 425$ km s$^{-1}$ for an ensemble of clouds as suggested by the width of the H 21 cm absorption line (Heckman *et al.* 1983*a*). Within a region of similar size, the absolute magnitude of an average giant elliptical galaxy is $M_K \approx -23.0$ (Lebofsky and Eisenhardt 1985); the stellar luminosities of the nuclei of these galaxies therefore significantly exceed those of the brightest type of galaxy known from optical studies.

The multiaperture photometry at 2 $\mu$m shown in Table 2

TABLE 3

PROPERTIES OF STARBURST GALAXIES

| Property | M81 | M82 | NGC 3690 | NGC 1614 | Arp 220 | NGC 6240 |
|---|---|---|---|---|---|---|
| $N$ flux in 6″ beam (Jy) | 0.15[a] | 6.4[b] | 1.1[c] | 0.63[d] | 0.21[e] | 0.25[e] |
| $Q$ flux in 6″ beam (Jy) | 0.31[a] | 24[b] | 2.3[c] | 3.1[d] | 2.5[e] | 2.3[f] |
| $cz$ (km s$^{-1}$) | 88 | 322 | 3300 | 4643 | 5420 | 7362 |
| $D$ (Mpc) | 3.1 | 3.1 | 41 | 58 | 68 | 92 |
| $M_K$ (observed) | −22.2[g] | −22.4[g] | −23.3[c] | ... | −23.3[e] | −24.6[e] |
| $L_N$ ($L_\odot$) | $5 \times 10^6$ | $1 \times 10^9$ | $8 \times 10^9$ | $9 \times 10^9$ | $4 \times 10^9$ | $9 \times 10^9$ |
| $L_{IR}$ ($L_\odot$) | $\leq 10^8$ [h] | $3 \times 10^{10}$ [i] | $3 \times 10^{11}$ [c] | ... | $1 \times 10^{12}$ [j] | $5 \times 10^{11}$ [k] |
| CO depth (mag) | 0.13[e] | 0.25[e] | ... | ... | 0.20[e] | 0.23[e] |
| $\tau_{Si}$ | ... | 1.8[l] | 1.5[c] | 1.2[m] | ≥1.8[e] | 2.2[e] |
| Br$\gamma$ ($10^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | <2[n] | 22[n] | 10[o] | 5.4[m] | 3[e] | 3.1[e] |
| He I ($10^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | <2[n] | 12[n] | ... | ... | ... | 3.8[e] |
| $H_2$ $S$(1) ($10^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | <2[n] | <4[n] | 6[o] <3[e] | ... | 7.2[e] | 39[e] |

NOTE.— Line strengths reported are for an 8″.7 aperture.
[a] Dyck, Becklin, and Capps 1978.
[b] Rieke *et al.* 1980.
[c] Gehrz, Sramek, and Weedman 1983.
[d] Rieke and Low 1972.
[e] This work.
[f] Wright, Joseph, and Meikle 1984.
[g] Aaronson 1978.
[h] Harvey, Gatley, and Thronson 1978.
[i] Telesco and Harper 1980.
[j] Soifer *et al.* 1984.
[k] *IRAS Circ.*, No. 4.
[l] Gillett *et al.* 1975.
[m] Aitken, Roche, and Phillips 1981.
[n] Our unpublished work.
[o] Fischer *et al.* 1983.

allows us to localize the stellar population. Both galaxies show compact nuclei with diameters of about 6″–8″ (Arp 220) and 4″ (NGC 6240), similar in size to the 10 $\mu$m sources and again corresponding to 2–3 kpc.

### *b) Active Galaxies or Starbursts?*

The most basic question about these galaxies is whether their luminosities are produced predominantly by an active nucleus—e.g., whether they are Seyfert galaxies—or by an exceptionally strong burst of star formation. Soifer *et al.* (1984) posed this question but were unable to answer it.

The most generally accepted discriminator between starburst and active galaxies is the broad spectral lines seen in Seyfert galaxies. However, this criterion should be used with caution because the supernova explosions in starbursts release large amounts of kinetic energy into the interstellar medium (e.g., Rieke *et al.* 1980), and in exceptionally powerful starbursts broad-line components might result. In these starbursts, narrow lines can be counted on only during the earliest stages, before the supernova rate becomes high. In both Arp 220 and NGC 6240 the lines are of width typical for type 2 Seyfert galaxies. However, unlike the relatively compact broad-line regions of Seyfert galaxies, the broad lines extend over regions of size similar to those of the 2 and 10 $\mu$m nuclear sources (Fosbury and Wall 1979; Heckman *et al.* 1983*a*, *b*).

A second commonly used criterion is the relative strengths of emission lines and other spectral features. In the infrared, the similarity between the spectra of these galaxies and that of M82, the prototypical starburst galaxy, is very close, including strong silicate absorption and strong emission at 3.27 $\mu$m. Deep 10 $\mu$m absorption features are relatively uncommon in Seyfert galaxies and are ubiquitous in infrared starburst galaxies (Lebofsky and Rieke 1979; Roche *et al.* 1984; Cutri *et al.*, in preparation). The unidentified 3.27 $\mu$m feature, when observed in Seyfert galaxies, tends to be associated with star formation complexes around the nucleus rather than directly with the active source (Cutri *et al.* 1984).

In the optical, the differing natures of the ionizing continua should become apparent. The forbidden oxygen line ratios for NGC 6240 place it near the Liner region as defined by Heckman (1980); correction for reddening moves the galaxy closer to the center of this region. It is unclear whether Liners are excited collisionally (Heckman 1980) or by photoionization (e.g., Péquignot 1984). Using reddening-insensitive line ratios in the classification scheme of Baldwin, Phillips, and Terlevich (1981), NGC 6240 is well within the region of collisionally excited or shock-excited sources. This conclusion was reached previously by Fosbury and Wall (1979) and Fried and Schulz (1983). The forbidden oxygen line ratios for Arp 220 place it within the Seyfert galaxy region in Heckman's (1980) classification. In the scheme of Baldwin, Phillips, and Terlevich (1981), this galaxy is at least near the edge of the region of galaxies ionized by power-law continua and will lie well within this region if H$\beta$ is weaker than our upper limit. We conclude that Arp 220 probably contains a nonthermal nuclear source; however, its spectrum is sufficiently peculiar that other excitation mechanisms may contribute significantly.

Our measurements show that the bright 2 $\mu$m sources are extended over about 2 kpc in the nuclei of these galaxies; at 10 $\mu$m the sources have a similar extent. The infrared fluxes are obviously not the nonthermal emission of compact, active nuclei. If these fluxes were thermal reradiation by gray dust grains surrounding such a nucleus, diameters of only $\sim$0.3 and $\sim$8 pc would be expected at 2.2 and 10 $\mu$m, respectively. Dust grains with extreme optical properties could produce a larger source, but a source of 2 kpc extent would be difficult and a source of this diameter at both wavelengths would require a very contrived model. Therefore, our observations imply the presence of an extended luminosity source.

The near-infrared emission of starburst and other nonactive galaxies is produced by red giant and supergiant stars with strong CO bands in absorption at 2.3 $\mu$m. We find these features in the spectra of both galaxies, demonstrating that their extraordinary near-infrared luminosities are produced by stars. Since the absolute magnitudes of these nuclear stellar populations are much brighter than those for any other nonstarburst galaxies, this result strongly favors the starburst hypothesis. In fact, after correction for reddening, the luminosity of the inner 4 kpc diameter region in NGC 6240 in red giants and supergiants alone is about $3 \times 10^{11}$ $L_{\odot}$, nearly equivalent to its far-infrared luminosity. For Arp 220 the inner 3 kpc has a red stellar luminosity of about $8 \times 10^{10}$ $L_{\odot}$.

A refinement of these arguments can be made if stellar features associated specifically with young stars are detected. The detection of strong Balmer absorption features in the optical is generally accepted as proof of recent star formation, although these features are absent in some starburst galaxies because of heavy extinction in and near the star-forming regions. A similar discriminator is based on the strength of the CO bands at 2.3 $\mu$m. For galaxy nuclei not undergoing strong starbursts, these bands are generated by similar populations of red giants and are of virtually identical strength regardless of galaxy type (see, e.g., Aaronson 1978; Frogel *et al.* 1978). For the strong starburst galaxies M82 and NGC 253, the 2 $\mu$m fluxes contain a substantial contribution from red supergiants associated with the starburst. Since the CO bands in the spectra of these stars are stronger than those in red giants, stronger CO bands would be expected in the galaxy spectra and are, in fact, observed (Rieke *et al.* 1980). For Arp 220, H$\beta$ appears in absorption, indicative of an exceptionally luminous population of young, hot stars. For both Arp 220 and NGC 6240, the CO bands are much stronger than in nonstarburst galaxies such as M81. Table 3 shows that the CO band strengths are closely comparable to those for M82.

In agreement with the suggestions of Baan and Haschick (1984) and Wright, Joseph, and Meikle (1984), we conclude that starbursts of exceptional strength are occurring in these galaxies. In the discussion below, we will compare Arp 220 and NGC 6240 in detail with the prototype starburst galaxy M82, with the exceptionally luminous starburst in NGC 3690 (Gehrz, Sramek, and Weedman 1983), and with the infrared-luminous galaxy NGC 1614 (Rieke and Low 1972), which has been studied in less detail but also appears to be undergoing a starburst (Heckman *et al.* 1983*b*). The properties of these galaxies are summarized in Table 3. Although our observations point to powerful starbursts in both galaxies, particularly for Arp 220 they suggest that the starbursts are accompanied by an active nucleus. This possibility will be considered after discussion of detailed starburst models.

### c) *Parameters for Models*

The above discussion establishes the existence of starbursts in these galaxies; to understand quantitatively conditions in the starbursts and their contributions to observed properties of the galaxies, detailed models must be constructed based on realistic star formation rates, IMF, and stellar evolution. Such models were calculated with an improved version of the computer code discussed by Rieke *et al.* (1980) (details of starburst calculations are being prepared for publication elsewhere). The basic output parameters from the models were (1) bolometric luminosity; (2) absolute magnitude of stellar population at 2 $\mu$m; (3) CO band depth; and (4) ionizing flux. The relevant observations for comparison with these predictions have been discussed above.

Estimates of both the ionizing fluxes and the absolute magnitudes must be corrected for the heavy extinction of the nuclei of the galaxies. In the starburst models, many conclusions can be drawn from the ratio of ionizing flux to the flux from red supergiants; if both estimates are based on measurements at the same wavelength, the effects of extinction will cancel to first order. We therefore use the Br$\gamma$ line (rest wavelength 2.16 $\mu$m) to determine the ionizing flux for comparison with the absolute magnitude at $K$ (2.2 $\mu$m). However, even in this case the likelihood of nonuniform extinction and the spatial separation of associations of hot stars and red supergiants will result in some uncertainty in the ratio of fluxes.

Some parameters—most important, the ratio of far-infrared luminosity to ultraviolet and 2 $\mu$m stellar luminosities—depend directly on the level of extinction, which appears to be large. The deep silicate absorptions for both galaxies suggest that along some lines of sight the extinction is of the order $A_v = 30$ or more (Rieke and Lebofsky 1985). Since the absorption feature will tend to be produced in the densest interstellar clouds, we take this estimate as an upper limit to the general extinction. However, at least in the cases of M82 and NGC 253, it has been found that the extinction to the starburst regions in general is close to that estimated from the strength of the silicate absorption.

Examination of the near-infrared colors of the galaxies shows that the derived extinction increases rapidly as estimates are based on measurements at increasingly longer wavelengths. For NGC 6240, Fosbury and Wall (1979) estimated an extinction of $A_V = 4$ from the H$\alpha$/H$\beta$ ratio. We find that H$\alpha$/Br$\gamma$ also corresponds to $A_V = 4$, assuming conditions of case B radiative recombination. For Arp 220, H$\alpha$/Br$\gamma$ corresponds to $A_V = 7$. For both galaxies, $A_V \sim 3$ and $A_V \sim 7$ can be calculated from the colors from $J$ to $H$ and $H$ to $K$, respectively, assuming that the intrinsic colors are typical of other galactic nuclei but are reddened by the extinction law proposed by Rieke and Lebofsky (1985). Using continuum levels estimated from our spectrophotometry, we estimate from the colors between $K$ (2.2 $\mu$m) and $L$ (3.5 $\mu$m) that $A_V \sim 11$ for Arp 220 and $A_V \sim 17$ for NGC 6240. From the slope of the continuum between 3.2 and 3.6 $\mu$m, we find $A_V = 15$–$20$ for both galaxies. This behavior mimics that of M82, where it arises from optical depth effects that cause the extinction to be underestimated at short wavelengths (Rieke *et al.* 1980). Judging from M82, where the stellar continuum dominates the spectrum through 5 $\mu$m (Rieke *et al.* 1980), the best estimate of extinction should be based on the color difference between $K$ and $L$, 2.2 and 3.5 $\mu$m, and on the spectrophotometry near 3.5 $\mu$m.

From these data, we adopt $A_V = 15$ for NGC 6240 and $A_V = 10$ for Arp 220. The resulting estimates of the intrinsic line strengths and absolute magnitudes are given in Table 4. This table summarizes the other parameters that provide the basic constraints on starburst models for the nuclei of these galaxies.

### d) *Starburst Models*

A total of 135 starburst models were generated and compared with the parameters in Table 4. In addition to the constraints from our observations discussed above, we placed an upper limit of $10^{10}$ $M_{\odot}$ on the mass participating in the starburst, reflecting the lack of any evidence for extreme rotation velocities in the spectral lines (Fosbury and Wall 1979; Tifft 1982; Heckman *et al.* 1983*b*; Fried and Schulz 1983). The free parameters in the models are (1) the time since the initiation of the starburst; (2) the rate of star formation as a function of time; and (3) the shape of the IMF. The models included the possibility of exponentially falling or rising stellar birthrate, constant birthrate, or a single short-duration (delta function) burst of star formation. Initial mass functions were considered similar to that in the solar neighborhood and with power laws of various slopes. In the latter cases, a uniform upper mass

TABLE 4

PARAMETERS FOR STARBURST MODELS

| Parameter | Arp 220 | NGC 6240 |
|---|---|---|
| $L(L_\odot)$ | $1 \times 10^{12}$ | $5 \times 10^{11}$ |
| $A_V$ | 10 | 15 |
| $M_K$ | −24.5 | −26 |
| Brγ ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | 0.8 | 1.4 |
| $L_{Br\gamma}$ ($10^{40}$ ergs s$^{-1}$) | 4.4 | 14 |
| UV flux at source (photons s$^{-1}$) | $3.4 \times 10^{54}$ | $1.5 \times 10^{55}$ |
| CO depth (mag) | 0.20 | 0.23 |
| $S(0)$ 1–0 ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | 0.6 | 4.9 |
| $S(1)$ 1–0 ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | 2.0 | 18.3 |
| $S(2)$ 1–0 ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | ... | 3.4 |
| He I ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | ... | 1.8 |

cutoff of 31 $M_\odot$ was assumed, but lower cutoffs ranging from 0.09 to 6 $M_\odot$ were tried.

We found that the observed characteristics of NGC 6240 could be fitted satisfactorily by starbursts similar to scaled-up versions of those computed earlier for M82 (Rieke *et al.* 1980). The successful models require most of the available $10^{10}$ $M_\odot$. Potentially somewhat less mass would be needed and a stronger Brγ line produced if stars more massive than 31 $M_\odot$ had been included in the calculations although the agreement between Brγ line strengths and the model prediction would go against this. It was impossible to stay within the mass constraints without strong enhancement of formation of massive stars compared with the solar neighborhood IMF, either by lower mass cutoffs well above solar mass or by power-law slopes less than (flatter than) the solar neighborhood value at high masses, or both. The continuously decreasing stellar birthrates produce clearly superior fits to the data. Furthermore, if the birthrate is assumed to decay exponentially, time constants between 20 and 40 Myr produce the best fits. All reasonable models were found to have ages between 60 and 100 Myr. From our estimates that the emitting regions are about 2 kpc in diameter, the rate of star formation per unit volume is therefore similar to that in M82, but the volume is 10–20 times larger.

The similarity of the starburst models for NGC 6240 and M82 implies that the supernova rate and luminosity of supernova remnants should scale with the luminosity in hot stars and hence with the far-infrared luminosity. For M82 and potentially for NGC 6240, the radio flux at low frequencies is attenuated by progressive free-free absorption (Hargrave 1974; Kronberg and Wilkinson 1975). We therefore compare fluxes at 5 GHz: 4 Jy for M82 (Kellermann and Pauliny-Toth 1971) and 80 mJy for NGC 6240 (Condon *et al.* 1982). Scaling by the far-infrared luminosities indicated in Table 3, we find that the 5 GHz luminosities of the two galaxies are equivalent to within 10%. Multiaperture fluxes for the radio flux can be taken from the work of Fosbury and Wall (1979) and Condon *et al.* (1982) at 1.4 GHz, giving fluxes within apertures of 10″, 5″, and 2″ of 350, 230, and 63 mJy, respectively. The size of the radio source therefore agrees well with that of the 10 μm source. Thus, the radio observations provide further confirmation that the dominant energy-generating process in NGC 6240 is an immense starburst.

For Arp 220, a broad range of starburst models were consistent with the observed parameters. Again, models with a decreasing rate of star formation were the most successful. All these models also require IMFs with power-law slopes of 1.5 or flatter, thus greatly enhancing the number of massive stars compared with the solar neighborhood IMF. Satisfactory fits are achieved for starbursts of ages 30–100 Myr; assuming that these bursts have decayed exponentially, time constants range from 10 to 75 Myr.

The one shortcoming of the starburst models of Arp 220 was that the models with sufficient bolometric luminosity tended to be at least twice as bright near 2 μm as our estimates from the observations. Because the relative numbers of hot and cool stars are constrained by the extinction-independent ratio of Brγ to $K$ flux, even extreme adjustments to the starburst models are unlikely to remove this discrepancy. There are only two likely explanations: (1) we have underestimated the extinction to the starburst regions by a factor of about 2 or (2) about half of the bolometric luminosity is generated in some other way, such as by an active nucleus.

The 5 GHz luminosity of Arp 220 scales with far-infrared luminosity from that of M82 to within about 35%. However, the radio source appears to be significantly more compact than the 10 μm source (Condon 1980; Baan and Haschick 1984). This behavior could result if the radio source is the site of an incredibly intense starburst at a sufficiently advanced evolution that many supernovae have occurred, with the surrounding areas the sites of more recent starbursts. This picture is consistent with the model advanced to explain the OH "megamaser" emission from this galaxy (Baan and Haschick 1984). Alternatively, some of the radio emission may be associated with an active nucleus.

In view of the complications in modeling Arp 220, it is worth reemphasizing that our observations require the presence of a very powerful starburst (§ III*b*). A more detailed understanding of the extinction, the structures of the infrared and radio sources, and the emission-line spectrum is needed to determine whether this starburst accounts for 30%–50% of the luminosity of the galaxy, or for virtually all of it.

### *e) Molecular Hydrogen Emission*

Both Arp 220 and NGC 6240 have very strong emission lines due to molecular hydrogen. These lines are observed in a variety of Galactic sources (Shull and Beckwith 1982) and in the external galaxies NGC 1068 (Thompson, Lebofsky, and Rieke 1978; Hall *et al.* 1981) and NGC 3690 (Fischer *et al.* 1983). As indicated in Table 3, we have reobserved the latter galaxy and set a limit in an 8″.7 beam that is a factor of 2 below the claimed detection level. Since the previous detection was with much larger beams than ours, it seems that the molecular hydrogen source is extended or displaced from the point we measured. Molecular hydrogen is not seen in M82 or NGC 253. We believe that these lines occur only rarely with sufficient strength to be detected in external galaxies; the currently detected examples imply that the lines are generally associated with very high bolometric luminosities.

The spectacular $H_2$ luminosities of Arp 220 and especially NGC 6240 can be interpreted through several approaches. First, a direct comparison can be made with sources of the $H_2$ line in the Galaxy. After correction for extinction, the total luminosity in the $H_2$ 1–0 $S(1)$ line from the Orion Molecular Cloud is approximately 20 $L_\odot$ (Beckwith *et al.* 1983). If both the H Br$\gamma$ and the $H_2$ 1–0 $S(1)$ lines in NGC 6240 undergo the same level of extinction, the implied luminosity of the latter is about $4 \times 10^8$ $L_\odot$, or $2 \times 10^7$ Orion sources. If identified with the number of active star-forming regions, this luminosity would imply 20–30 times more recently formed $T \sim 35{,}000$ K stars than are predicted by the starburst models and about 10 times as many as are needed to account for the entire Br$\gamma$ luminosity by photoionization and recombination. In the case of Arp 220, the analogy with the Orion Molecular Cloud implies a factor of 3 discrepancy between the $H_2$ and Br$\gamma$ strengths. $H_2$ emission can also be produced by the interaction of a supernova remnant with the surrounding molecular gas; Treffers (1979) has measured a mean intensity of $1.1 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ in the 1–0 $S(1)$ line from the remnant IC 443. Although the mean surface brightness from the nuclear region of NGC 6240 is 10 times larger, it has been suggested by Lepp and McCray (1983) that a significant fraction of the luminosity of X-ray sources buried within molecular clouds (such as supernova remnants [cf. Shull 1980; Wheeler, Mazurek, and Sivaramakrishnan 1980]) will be converted into $H_2$ line emission.

A more fundamental approach is to ask how much $H_2$ emission could be produced by molecular gas directly associated with the hot stars responsible for the Br$\gamma$ emission. If the Br$\gamma$ emission arises in spherical H II regions, and if each such region drives a relatively weak (i.e., nondissociating) shock into a thick surrounding molecular cloud, then the surface area of the shock-heated $H_2$ can be directly related to the size of the H II region and thus to the ionizing luminosity of its central star. Based on a simple model of this process (to be published elsewhere), it can be shown that the Br$\gamma$ luminosity, $L$(Br$\gamma$), and that of an associated $H_2$ line are related by

$$\frac{L(\mathrm{H_2})}{L(\mathrm{Br}\gamma)} \approx 5 \times 10^{25}\ H(v_s)v_s^{-2}(n_e S_0)^{-1/3}\ , \qquad (1)$$

where $v_s$ is the shock speed in km s$^{-1}$, $H(v_s)$ is a function of $v_s$ only, $n_e$ is the mean electron density of the H II region, and $S_0$ is the luminosity of the ionizing photons per second from its central star. For the 1–0 $S(1)$ line, $H(v_s)v_s^{-2} \approx (5\text{–}6) \times 10^{-11}$, almost independently of $v_s$ in the range 10–20 km s$^{-1}$. If all the Br$\gamma$ luminosity is supplied by $T = 35{,}000$ K stars ($S_0 = 8.9 \times 10^{48}$ s$^{-1}$) within a 1 kpc radius nuclear region, then $n_e > 20$ cm$^{-3}$ and there is a strong upper limit $L(\mathrm{H_2})/L(\mathrm{Br}\gamma) < 0.05$.

The postulated molecular shells around H II regions will also be exposed to large fluxes of 900–1100 Å photons, which can excite the infrared lines of $H_2$ by absorption and fluorescence (Black and Dalgarno 1976). Detailed calculations of this process (to be published elsewhere) show that the $H_2$ and Br$\gamma$ line luminosities are related by $L(\mathrm{H_2})/L(\mathrm{Br}\gamma) = G(T)$, where $G$ is a function of the effective temperature of the exciting star and it has been assumed that all photons in the band 912–1100 Å escape the H II region to enter the surrounding molecular cloud. If most of the Br$\gamma$ luminosity is accounted for by stars with $T > 35{,}000$ K, then $G(T)$ can be no larger than unity. For stars with $T < 25{,}000$ K, it is possible to obtain values $G(T) \geq 9$, consistent with the observations of NGC 6240. However, more than $10^8$ such stars would be required to produce the Br$\gamma$ luminosity, and the IMF would require a sharp upper cutoff at a fairly low mass. Such restrictions are difficult to reconcile with the starburst models and with the detection of He I in the spectrum of NGC 6240.

Since neither of the above calculations has accounted satisfactorily for the $H_2$ as the direct product of the starburst, we have tried to relate it to a global phenomenon such as interaction between a disk of molecular gas and a shock of galaxian dimensions produced, for example, by the interaction between two galaxies. We can then write $L(\mathrm{H_2}) \sim 4\pi\sigma I$, where $I$ is the mean intensity on an $H_2$ line emerging from a layer of shock-heated molecular gas and $\sigma$ is the total surface area of such gas exposed to shock fronts. To allow for shocks with velocities greater than 20 km s$^{-1}$, it is necessary to consider molecular dissociation and re-formation in the cooling region behind the shock (Hollenbach and McKee 1979, 1980). The description of such shocks is necessarily quite complicated. In NGC 6240, the exposed surface area cannot much exceed that of one side of a thin disk 2 kpc in diameter, the size of the observed emission region. The $H_2$ luminosity in the 1–0 $S(1)$ line, $1.6 \times 10^{42}$ ergs s$^{-1}$, thus requires a mean intensity $I \approx 4 \times 10^{-3}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The models of hydromagnetic shocks computed by Draine, Roberge, and Dalgarno (1983) show that this $H_2$ line intensity can be provided by a 50 km s$^{-1}$ shock propagating into a cloud of density $n = 10^4$ cm$^{-3}$ or by a 25 km s$^{-1}$ shock and a cloud of density $10^6$ cm$^{-3}$. It is not necessary that the nuclear disk be completely filled with molecular cloud material at these densities, only that the indicated combination of mean cloud density, exposed cloud surface area, and shock speed be satisfied. If a disk of 2 kpc diameter and thickness $h$ were fully filled with gas at density $n$, the mass of gas implied would be $m_{\mathrm{gas}} = 8 \times 10^{10}(n \times 10^{-4})h$ (100 pc)$^{-1}$ $M_\odot$. This amount of gas is comparable to that consumed in the starburst, and could be consistent with an episode of star formation having an overall efficiency of the order of 50% in converting gas to stars (as found previously for M82; Rieke *et al.* 1980). The presence of such large quantities of disturbed interstellar material in the nuclei of these galaxies is also supported by the exceptionally strong and broad H I absorption seen in their radio spectra (Heckman *et al.* 1983*a*; Mirabel 1982).

The total shock energy to accompany the $H_2$ emission is of the order of the far-infrared luminosity of these galaxies. However, Draine, Roberge, and Dalgarno (1983) argue that the energy exchange between the shock and interstellar dust will be very inefficient and that the dust is likely to be heated to temperatures only of the order of 15 K. Nonetheless, the possibility of a shock-heated contribution to the far-infrared emission deserves further consideration, particularly for Arp 220.

It is tempting to speculate that a galaxy-galaxy interaction will produce shock waves large enough to cover the entire nuclear region of a galaxy. It appears that $H_2$ luminosities like that in NGC 6240 can be explained only if such a shock propagates face-on to the nuclear gas disk: in this sense, such intense $H_2$ emission may be as rare as the occurrence of the most favorable geometry of interacting galaxy pairs. The preceding discussion suggests, however, that even isolated starburst galaxies could produce $H_2$ emission at a level of a few percent of the Br$\gamma$ luminosity.

### *f*) *Evolution of Arp 220 and NGC 6240*

The immense starbursts occurring in the nuclei of Arp 220, NGC 6240, and the other galaxies listed in Table 3 have interesting implications for the pasts and futures of the host galaxies.

In addition to the galaxies listed in Table 3, it has been suggested that NGC 1097 (Telesco and Gatley 1981) and NGC 1068 (Telesco, Becklin, and Wynn-Williams 1980) have only slightly less luminous starbursts around their nuclei. From the six known within 100 Mpc, the space density of such events must be $\geq 1.5 \times 10^{-6}$ Mpc$^{-3}$. Since some members of the class have spectral properties that could be confused with those of Seyfert or other active galaxies (broad emission lines, Liner spectra), this number may be significantly underestimated; a more definitive estimate awaits the release of the *IRAS* catalog. Our starburst models indicate that the lifetime of this phenomenon is $\leq 10^8$ years; assuming that we are sampling a typical rate, during the past $10^{10}$ years the density of galactic nuclei that have gone through super starbursts should be $\geq 1.5 \times 10^{-4}$ Mpc$^{-3}$. Since the space density of significant galaxies ($M_v < -19$) is about $2 \times 10^{-2}$ Mpc$^{-3}$, roughly 1% of such galaxies should have undergone such events at some time since their formation, even assuming that the incidence of super starbursts was no higher in the past than now.

To sustain a super starburst, nearly $10^{10}$ $M_\odot$ of interstellar material must be injected into the nucleus of the galaxy over a period $\leq 10^8$ years—i.e., an average inward mass flow $\geq 100$ $M_\odot$ yr$^{-1}$ must be maintained. The question of injecting large amounts of matter into galactic nuclei has been studied extensively as part of the process powering active galaxies and QSOs. Because of conservation of angular momentum, mass flows larger than 0.1–1 $M_\odot$ yr$^{-1}$ appear to be difficult to produce without a major disturbance from outside the galaxy (Norman and Silk 1983). These authors demonstrate that relatively small departures from axial symmetry in the gravitational potential of a galactic nucleus can alleviate the problems with angular momentum and can lead to amplification of the mass flow rate by as much a factor of 10. Silk and Norman (1981) have demonstrated that a galaxy collision can produce such a non-axisymmetric potential. They did not consider large perturbations, such as may be required to explain the large mass flows seen in Arp 220 and NGC 6240. We note that the X-ray emission from dominant cluster galaxies may require mass flows comparable to those seen in Arp 220 and NGC 6240 (Canizares *et al.* 1979; Mushotzky *et al.* 1981; Fabian *et al.* 1981). Both Arp 220 and NGC 6240 appear to be double systems undergoing strong interactions, and most of the other super starbursts are occurring in systems that are interacting or show other morphological peculiarities. Using assumptions consistent with ours, Toomre (1977) has estimated that the rate of intense spiral galaxy interactions (normally leading to the merger of the galaxies) is high enough that about 6% of the NGC galaxies should have undergone such an event in their lifetimes. Thus, the incidence of intense interactions is consistent with the density of super starbursts and, to order of magnitude, about 10% of such interactions appear to lead to such a starburst.

Turning around the above arguments, the presence of such high stellar luminosities in the nuclei of interacting galaxies places a lower limit of a few billion solar masses on the amount of interstellar material that has been injected into these regions. Adopting the popular picture that many normal-appearing galaxies have nuclear black holes that would flare into active nuclei if there were adequate material for them to accrete, the interaction might be expected to trigger this form of activity to accompany the starburst. Such an event may be occurring in Arp 220.

As a consequence of the immense number of massive stars in the nuclei of Arp 220, NGC 6240, and presumably other super starburst galaxies, our starburst models show that about $10^9$ $M_\odot$ of stellar remnants must be left in the starburst region after the burst has died out and the massive stars have completed their evolution. Thus, conditions after the starburst may closely approximate the initial conditions assumed by Weedman (1983). He argued that the dynamical evolution of a nucleus with its mass divided roughly equally between old stars of $\leq 1$ $M_\odot$ and stellar remnants of $\sim 5$ $M_\odot$ would lead to formation of an active galaxy nucleus. A more thorough treatment of this suggestion seems warranted.

## IV. CONCLUSIONS

We have studied the nuclei of the exceptionally luminous interacting galaxies Arp 220 and NGC 6240 through detailed observations in the near- and middle-infrared. We find the following:

1. For NGC 6240 virtually all the far-infrared output of $5 \times 10^{11}$ $L_\odot$ and the near-infrared output of about $3 \times 10^{11}$ $L_\odot$ are produced as a result of a powerful starburst, involving the conversion of nearly $10^{10}$ $M_\odot$ of gas into stars.
2. Except for size, this starburst is very similar to the one occurring in M82. As in M82, the formation of solar-mass stars is suppressed compared with the initial mass function in the solar neighborhood; the starburst lifetime is of the order of $10^7$–$10^8$ years; the high rate of supernova explosions has stirred up the interstellar medium to velocities of hundreds of km s$^{-1}$ (accounting for the broad emission lines); and supernova remnants account satisfactorily for the radio emission.
3. For Arp 220 a starburst contributes substantially to the far-infrared luminosity of $10^{12}$ $L_\odot$. There is also evidence for an active nucleus; its role in the energetics of the galaxy relative to the starburst needs to be clarified by further observations.
4. For both galaxies there is exceedingly strong emission by shocked molecular hydrogen. This emission appears to be excited in the collision of the interstellar clouds of the interacting galaxies.
5. The galaxy collision is probably also responsible for injecting the material into the nuclei of the galaxies that is needed to sustain the starbursts. Detailed theoretical study is needed urgently to clarify how this process occurs and how it leads to the efficient formation of massive stars that is required to explain the properties of these and other galaxies.

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## REFERENCES


Aaronson, M. 1978, Ph.D. thesis, Harvard University.
Aitken, D. K., Roche, P. F., and Phillips, M. M. 1981, *M.N.R.A.S.*, **196**, 101P.
Baan, W. A., and Haschick, A. D. 1984, *Ap. J.*, **279**, 541.
Baldwin, J. A., Phillips, M. M., and Terlevich, R. 1981, *Pub. A.S.P.*, **93**, 5.
Becklin, E. E., DePoy, D., and Wynn-Williams, C. G. 1984, Paper presented at the Infrared Detector Workshop, Laramie, Wyoming, May 15–16, 1984.
Beckwith, S., Evans, N. J., Gatley, I., Gull, G., and Russell, R. W. 1983, *Ap. J.*, **264**, 152.
Bierman, P. 1984, preprint.
Black, J. H., and Dalgarno, A. 1976, *Ap. J.*, **203**, 132.
Campins, H., Rieke, G. H., and Lebofsky, M. J. 1984, in preparation.
Canizares, C. R., Clark, G. W., Markert, T. H., Berg, C., Smedira, M., Bardas, D., Schnopper, H., and Kalata, K. 1979, *Ap. J. (Letters)*, **234**, L33.
Condon, J. J. 1980, *Ap. J.*, **242**, 894.
Condon, J. J., Condon, M. A., Gisler, G., and Puschell, J. J. 1982, *Ap. J.*, **252**, 102.
Cutri, R. M., Rudy, R. J., Rieke, G. H., Tokunaka, A. T., and Willner, S. P. 1984, *Ap. J.*, **280**, 521.
Draine, B. T., Roberge, W. G., and Dalgarno, A. 1983, *Ap. J.*, **264**, 485.
Dyck, H. M., Becklin, E. E., and Capps, R. W. 1978, *Bull. A.A.S.*, **10**, 422.
Fabian, A. C., Hu, E. M., Cowie, L. L., and Grindlay, J. 1981, *Ap. J.*, **248**, 47.
Fischer, J., Simon, M., Benson, J., and Solomon, P. M. 1983, *Ap. J. (Letters)*, **273**, L27.
Fosbury, R. A. E., and Wall, J. V. 1979, *M.N.R.A.S.*, **189**, 79.
Fried, J. W., and Schulz, H. 1983, *Astr. Ap.*, **118**, 166.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Gehrz, R. D., Sramek, R. A., and Weedman, D. W. 1983, *Ap. J.*, **267**, 551.
Gillett, F. C., Kleinmann, D. E., Wright, E. L., and Capps, R. W. 1975, *Ap. J. (Letters)*, **198**, L65.
Hall, D. N. B., Kleinmann, S. G., Scoville, N. Z., Ridgway, S. T. 1981, *Ap. J.*, **248**, 898.
Hargrave, P. J. 1974, *M.N.R.A.S.*, **168**, 491.
Harvey, P. M., Gatley, I., and Thronson, H. A. 1978, *Bull. A.A.S.*, **9**, 629.
Harwit, M., and Pacini, F. 1975, *Ap. J. (Letters)*, **200**, L127.
Heckman, T. M. 1980, *Astr. Ap.*, **87**, 152.
Heckman, T. M., Balick, B., van Breugel, W. J. M., and Miley, G. K. 1983*a*, *A.J.*, **88**, 583.
Heckman, T. M., Miley, G. K., van Breugel, W., and Butcher, H. R. 1981, *Ap. J.*, **247**, 403.
Heckman, T. M., van Breugel, W., Miley, G. K., and Butcher, H. R. 1983*b*, *A.J.*, **88**, 1077.
Hollenbach, D., and McKee, C. F. 1979, *Ap. J. Suppl.*, **41**, 555.
———. 1980, *Ap. J. (Letters)*, **241**, L47.
Kellermann, K. I., and Pauliny-Toth, I. I. K. 1971, *Ap. Letters*, **8**, 15.
Kronberg, P. D., Biermann, P., and Schwab, F. R. 1981, *Ap. J.*, **246**, 751.
Kronberg, P. D., and Wilkinson, P. N. 1975, *Ap. J.*, **200**, 430.
Larson, R. B. and Tinsley, B. M. 1978, *Ap. J.*, **219**, 46.
Lebofsky, M. J., and Eisenhardt, P. R. M. 1985, *Ap. J.*, in press.
Lebofsky, M. J., and Rieke, G. H. 1979, *Ap. J.*, **229**, 111.
Lepp, S., and McCray, R. 1983, *Ap. J.*, **269**, 560.
Loose, H. H., Krugel, E., and Tutukov, A. 1982, *Astr. Ap.*, **105**, 342.
Mirabel, I. F. 1982, *Ap. J.*, **260**, 75.
Mushotzky, R. F., Holt, S. S., Smith, B. W., Boldt, E. A., and Serlemitsos, P. J. 1981, *Ap. J. (Letters)*, **244**, L47.
Norman, C., and Silk, J. 1983, *Ap. J.*, **266**, 502.
Péquignot, D. 1984, *Astr. Ap.*, **131**, 159.
Rieke, G. H., and Lebofsky, M. J. 1985, *Ap. J.*, **288**, 618.
Rieke, G. H., Lebofsky, M. J., and Low, F. J. 1984, in preparation.
Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. 1980, *Ap. J.*, **238**, 24.
Rieke, G. H., and Low, F. J. 1972, *Ap. J. (Letters)*, **176**, L95.
———. 1975, *Ap. J. (Letters)*, **200**, L67.
Roche, P. F., Aitken, D. K., Phillips, M. M., and Whitmore, B. 1984, *M.N.R.A.S.*, **207**, 35.
Shull, J. M. 1980, *Ap. J.*, **237**, 769.
Shull, J. M., and Beckwith, S. 1982, *Ann. Rev. Astr. Ap.*, **20**, 163.
Silk, J., and Norman, C. 1981, *Ap. J.*, **247**, 59.
Soifer, B. T., *et al.* 1984, *Ap. J. (Letters)*, **283**, L1.
Stone, R. P. S. 1977, *Ap. J.*, **218**, 767.
Strömgren, B. 1963, in *Stars and Stellar Systems*, Vol. **3**, *Basic Astronomical Data*, ed. K. Aa. Strand (Chicago: University of Chicago Press), p. 387.
Telesco, C. M., Becklin, E. E., and Wynn-Williams, C. G. 1980, *Ap. J.*, **241**, L69.
Telesco, C. M., and Gatley, I. 1981, *Ap. J.*, **247**, L11.
Telesco, C. M., and Harper, D. A. 1980, *Ap. J.*, **235**, 392.
Thompson, R. I., Lebofsky, M. J., and Rieke, G. H. 1978, *Ap. J. (Letters)*, **222**, L49.
Tifft, W. G. 1982, *Ap. J. Suppl.*, **50**, 319.
Toomre, A. 1977, in *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley, and R. B. Larson (New Haven: Yale University Observatory), p. 401.
Treffers, R. 1979, *Ap. J. (Letters)*, **232**, L17.
Weedman, D. W. 1983, *Ap. J.*, **266**, 479.
Weedman, D. W., Feldman, F. R., Balzano, V. A., Ramsey, L. W., Sramek, R. A., and Wu, C.-C. 1981, *Ap. J.*, **248**, 105.
Wheeler, J. C., Mazurek, T. I., and Sivaramakrishnan, A. 1980, *Ap. J.*, **237**, 781.
Wright, G. S., Joseph, R. D., and Meikle, W. P. S. 1984, *Nature*, **309**, 430.


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