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A SUBDUED INTERPRETATION OF THE VISUAL AND INFRARED EMISSION FROM MERGING GALAXIES: APPLICATION TO NGC 6240[1]

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ABSTRACT

Most past work on infrared-luminous galaxies ignored the contribution from older stars in heating the interstellar dust. Past work on galaxies of all types has also usually adopted a physically unrealistic model for the internal dust distribution, which can lead to a misinterpretation of broad-band colors. We present and discuss U (0.36 μm), R (0.65 μm), J (1.25 μm), H (1.65 μm), and K (2.2 μm) images of the merging, luminous galaxy NGC 6240, which allow us to study its stellar mass and light distribution, and to consider the usually neglected role of the older stellar population in heating the interstellar dust in merging systems. We estimate that older stars contribute between one-fifth and one-half of the total heating of the dust that is observed at far-infrared wavelengths in NGC 6240, while active star formation contributes roughly another fourth. Therefore, in contrast with almost every other recent study of this object, we argue that the system may not be undergoing a truly extraordinary burst of star formation but rather that much of the significant far-infrared emission is simply reradiated starlight from a badly disrupted and dispersed dusty interstellar medium. As part of our analysis, we develop a technique for estimating total stellar luminosities using visual and near-infrared photometry of systems whose star-forming histories and, hence, stellar populations are poorly known.

Discovering that stars are forming within a colliding galaxy pair is insufficient evidence that the collision triggered the star birth. The close association that is commonly drawn in the literature between mergers/interactions and consequent energetic "starbursts" tends to obscure the importance of the long-term, nearly normal stellar creation in gas-rich galaxies that may continue vigorously despite a collision. We derive a star formation rate for NGC 6240 and estimate that the efficiency of stellar creation is higher than that found for isolated galaxies, although this calculation has a large uncertainty. A normal formation efficiency indicates that new stars in the system would have been born anyway in the gas-rich precursors.

We take the opportunity to comment briefly on another popular "ultraluminous" "starburst" galaxy, Arp 220, and apply some of the same techniques to analyze this system. As with NGC 6240, there is little evidence for stellar formation at a rate sufficient to explain alone the observed far-infrared luminosity, and the radiation from the older stellar population probably exceeds that available from young stars. However, as opposed to NGC 6240, Arp 220 appears to require major additional heating sources other than light from old and very young stars. As with NGC 6240, the derived efficiency of star formation in Arp 220 has a large uncertainty, but it is very roughly in the range of that found for isolated, nearly normal galaxies.

We extend our detailed discussions of NGC 6240 and Arp 220 to other systems and attempt to quantify the role of enhanced interstellar absorption in merging galaxies; to derive the ratio of infrared to true stellar luminosity for a sample of normal, dwarf, and "superluminous" galaxies; and to point out our considerable disagreement with past work on this ratio. Large infrared-to-visual ratios in merging galaxies have been widely interpreted as indicating some unusual and very energetic process, but the ratios are as much a product of heavy interstellar obscuration as they are of luminous dust emission. In most previous work, the luminosity of the older stellar population in galaxies of all types and, therefore, its potential for heating the dusty interstellar medium, has been systematically underestimated and often overlooked.

Throughout our paper we emphasize the importance of proper treatment of the effects of a dusty interstellar medium. Uncertainties in the spatial distribution of galaxian dust are relatively unimportant for small values of the extinction, which is commonly assumed to be the case for normal isolated systems. However, for very dusty galaxies derivation of many source parameters requires knowledge of the relative star/dust distribution and a careful handling of the numerical approximations to the extinction. In our appendix, we briefly describe the effects of an alternative assumed dust distribution within galaxies.

We take several opportunities to argue against the use of M82 as a prototype for objects such as NGC 6240, Arp 220, and putative "starburst" galaxies in general.

Subject headings: galaxies: individual (NGC 6240, Arp 220, M82) — galaxies: interactions — galaxies: photometry — galaxies: stellar content — infrared: sources

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I. BACKGROUND

Nature often obliges scientists to study the bizarre, but she rarely insists on freakish interpretations. The unusual galaxy NGC 6240 (IC 4625, UGC 10592) is characterized by strong radio and infrared emission, a seriously disturbed morphological appearance with extensive faint tails, and some of the most heated nouns and adjectives in modern astrophysics. Its pair of nuclei, one of which is active, are separated by only about 2″ in projection (0.97 kpc at a distance of 100 Mpc, which we adopt throughout this work). Visual and near-infrared emission lines have been explained as arising from large-scale shocked gas (e.g., Fried and Schulz 1983; Lester, Harvey, and Carr 1988). Combined with its tortured appearance, these observations have led to the general conclusion that the system is the consequence of a merger between a pair of gas-rich galaxies (Zasov and Karachentsev 1979; Fosbury and Wall 1979; Fried and Schulz 1983; Joseph and Wright 1985; Rieke *et al.* 1985; Fried and Ulrich 1985).

Beyond being identified as a merging system, NGC 6240 has also been characterized as something like a "*super*-starburst" galaxy (e.g., Fried and Ulrich 1985; Rieke *et al.* 1985; Wright, Joseph, and Meikle 1984; Joseph and Wright 1985; Heckman, Armus, and Miley 1987; Heckman *et al.* 1987; Rieke 1987, 1988), indicating that its energetics are dominated by a short-lived, but extremely powerful, period of stellar creation directly caused by the collision. However, many investigators have pointed out that the strength of the hydrogen recombination lines is too low to be explained by the birth of sufficient numbers of massive, luminous stars to explain alone the infrared luminosity (e.g., DePoy, Becklin, and Wynn-Williams 1986; Fischer *et al.* 1987; Lester, Harvey, and Carr 1988). In addition, there is no evidence, over a large area, for a deep 2.3 μm CO absorption band, which would indicate a widespread, vigorous creation of young red supergiants (Doyon, Joseph, and Wright 1989). DePoy, Becklin, and Wynn-Williams (1986), for example, rejected the thesis of a "super" creation of massive stars and instead proposed that a luminous active nucleus similar to that found in Seyfert galaxies is the ultimate power source of the activity near the nuclei. Smith, Aitken, and Roche (1989) in turn disagreed with this interpretation, finding that the 10 μm spectrum of the inner core of the galaxy is characteristic of that expected from the birth of large numbers of stars. Leech *et al.* (1989) recognized the conflict between observations and a conventional "starburst" hypothesis, and proposed that a large fraction of young stars in infrared-luminous galaxies are deeply embedded within dust clouds which prevent the escape of visual and near-infrared hydrogen recombination lines. If correct, systematically low star formation rates will be derived.

Regardless of the energy source, much recent work has emphasized that the galaxy is extremely luminous at far-infrared wavelengths. Lester, Harvey, and Carr (1988) made a more conservative suggestion: although they also refer to NGC 6240 as "superluminous" in the title of their paper, they correctly point out in their text that the total luminosity of this merging galaxy pair is about equal to that of two luminous, but normal, spiral galaxies, presumably the precursors to this merging system (see also Zasov and Karachentsev 1979). In this explanation, the total luminosity of this system may be large, but not at all *ultra*. Rather, it is odd that so great a fraction is emitted at far-infrared wavelengths: very large ratios of observed infrared-to-visual light in NGC 6240 and other similar objects have been identified by many authors as indicating a remarkable or curious phenomenon. Identification of strong infrared emission as suggesting some excessively abnormal process is, however, tempered by the large variety of sources of heating for the interstellar dust (e.g., Harwit and Pacini 1975; Persson and Helou 1987; Boulanger and Pérault 1988; Harwit and Fuller 1988; Leisawitz and Hauser 1989; Thronson, Bally, and Hacking 1989; Bothun, Lonsdale, and Rice 1989; Rowan-Robinson and Crawford 1989; Rowan-Robinson 1990).

In the past two years, a number of reactionary challenges have been directed at the "starburst" paradigm for some very infrared luminous galaxies. First, Descartes *et al.* (1988) showed that in NGC 6240 the light from the older stellar population alone was almost sufficient to heat the dust observed at far-infrared wavelengths. Vigorous star formation of any kind, "bursting" or continuous, was not required. More recently, Bruzual, Magris, and Calvet (1988) and Disney, Davies, and Phillipps (1989) argued that the interstellar extinction and, consequently, the stellar luminosity in nearly normal galaxies have been significantly underestimated for decades. In this case, almost all the radiation from warm dust may be explained as heating by older stars. In merging or colliding galaxies, the disrupted interstellar medium is even more efficient at converting stellar light into the infrared.

We have investigated the structure and energetics of NGC 6240 using visual (U and R) and near-infrared (J, H, and K) imaging. At the longer wavelengths the significant dust obscuration is pierced and the core structure is revealed. From the near-infrared colors and emission, we are able to pursue the suggestion that light from the older stellar population in a pair of once normal, spiral galaxies is a major source of energy. In a dusty merged system, the disrupted and widely dispersed interstellar medium (ISM) efficiently converts stellar light into far-infrared emision because the absorption efficiency of dust is so large. It is likely that NGC 6240 is not the sole example of its type, and we comment briefly on one other popular "ultraluminous" galaxy, Arp 220. We also make a first approximation to estimate the contribution of the older stellar population to heating the dust in other very luminous systems. Finally, in our appendix, we briefly discuss the consequences of an alternative model for the distribution of dust within disrupted galaxies. This present paper is the detailed discussion of the investigation first given by Descartes *et al.* (1988).[6]

We shall follow conventional nomenclature in our discussion and use "starburst galaxy" to refer to a nearly galaxy-wide, short-lived period of enhanced star formation directly related to the merger in objects such as NGC 6240. As part of our analysis, we shall contrast the "burst" phenomenon with the long-term process of stellar creation, which (1) is very energetic in giant spirals, (2) may be continuing despite the effects of a merger, and (3), as with the light from the older stellar population, has been overlooked in past discussions of the energetics of objects such as NGC 6240 and Arp 220.

A variety of observed and derived source parameters from our work and the literature is presented in Table 1.

[6] We are sorely tempted to describe our all-time favorite object this month, NGC 6240, as either a "Holy Grail" or a "Rosetta stone" to emphasize to our colleagues that we *only* study fundamentally important galaxies. Unfortunately, the universe appears to be rapidly filling with such objects as judged by the references to these sources in the literature. As a consequence, we argue that NGC 6240 is still more significant and is, in fact, the eagerly sought and most rare *Holy Grail of Rosetta stones*!

TABLE 1

OBSERVED AND DERIVED SOURCE PARAMETERS

Parameter	Value
R.A. (1950), decl. (1950)[a]	$16^h50^m27^s.83$, $2°28'58''$
L_{IR}[b]	$4.8 \times 10^{11}\ L_\odot$
M_{bol}[c]	-23.9 ± 0.3, -23.5 ± 0.3
L_*[c]	$(2\text{–}3) \times 10^{11}\ L_\odot$
$F_{H\alpha}$[d]	1.5×10^{-12} ergs cm^{-2} s^{-1}
$L_{H\alpha}$[d]	$4.7 \times 10^8\ L_\odot$
$L_{*,\text{young}}$[e]	$\sim 1 \times 10^{11}\ L_\odot$
$\dot{M}_*$[f]	$\leq 65\ M_\odot$ yr^{-1}
$M(H_2)$[g]	$\sim 2 \times 10^{10}\ M_\odot$
M_*[h]	$3.3 \times 10^{11}\ M_\odot$

NOTE.—Assumed distance: 100 Mpc (1″ = 490 pc).

[a] Approximately midway between the pair of nuclei.

[b] Estimated for approximately 45–125 μm from *IRAS* data.

[c] Stellar bolometric magnitude and luminosity, derived from visual and near-infrared data, for two different assumed distributions of dust (§ III*b*). The uncertainty is estimated for the model used to derive M_{bol}. The uncertainty due to the dust obscuration and its distribution within NGC 6240 is probably larger.

[d] Hα flux and luminosity, uncorrected for extinction (Heckman, Armus, and Miley 1987). We estimate $A_{H\alpha} = 1.4$ mag.

[e] Derived luminosity of the newly formed stellar population (§§ III*b* and III*c*).

[f] Total star formation rate, derived from the corrected Hα line flux and a Salpeter distribution of stars from 0.1 to 100 $M_\odot$ (Gallagher, Hunter, and Tutukov 1984; Thronson and Telesco 1986). Upper limit from probability that not all the line flux is a consequence of ionization from young stars.

[g] Sanders and Mirabel 1985, but see also Maloney 1990 and Draine 1990 for a discussion of the wide range of possible values.

[h] Total stellar mass for the system, derived from our total *H*-magnitude and the model of Thronson and Greenhouse 1988.

II. THE OBSERVATIONS

a) Visual Observations

Images of NGC 6240 at ultraviolet and red wavelengths were obtained on the night of 1988 September 13 using the TI No. 1 CCD mounted at the prime focus of the CTIO 4 m telescope. The data were taken during the end of evening twilight under good conditions, with the full width at half-maximum of the seeing profiles of 1″.4 and 1″.3 at the shorter and the longer wavelengths, respectively. A pair of exposures each of 150 s duration was made using a liquid $CuSO_4$ + UG2 filter combination with a bandwidth of 670 Å, centered at 3575 Å. Five exposures of 45 s duration each and one of 300 s duration were obtained using the *R* filter described by Gullixson *et al.* (1990) with a bandwidth of 1400 Å, centered on 6500 Å.

The data were reduced following conventional techniques, accounting for overscan bias, readout drift corrections, overall bias offset, and flat fields. However, because the data on NGC 6240 were taken in conjunction with another, deep-imaging project (Guhathakurta, Tyson, and Majewski 1990), two advantages were gained in the reduction of the NGC 6240 data. Because the deep-imaging project required very high signal-to-noise calibration images, great care was taken in constructing the dome flat fields. For example, an *R*-band flat field was the product of a median filter of over 160 images of the CTIO "Great White Spot," while the *U* dome flat field was the product of over 120 such images. In addition, as a consequence of the multitude of images taken of nearly blank sky, the median filter of these images resulted in excellent "sky flats," which were used to correct for imperfections in the dome flat field. These sky flats were essential for the removal of the residual fringing evident in our nearly reduced images of the galaxy. The resultant images are sky-noise–limited.

Photometric calibration was obtained from repeated measurements of 10 Landolt standard stars spanning a large range in color ($U - R = 0.3$–4.1), observed over a wide range in air mass (1.1–2.6). NGC 6240 was observed at air mass 1.4. The magnitudes and $U - R$ colors were taken from a combination of Landolt (1973) and Gullixson *et al.* (1990). Because the standard stars were bright and saturated the CCD array in exposures of a few seconds, the telescope was defocused during the standard star observations. This permitted exposures of longer than a few seconds, reducing the photometric errors due to shutter timing and seeing fluctuations. Atmospheric transmission and color coefficients were determined from a simultaneous, least-squares solution to an equation relating instrumental magnitudes, air mass, and color to final standard magnitudes.

The data were combined by registering to the nearest 0.1 pixel, then co-added. Figure 1 (Plate 3) is the sum of the *U* images, with each inset printed on the same scale, but with different contrasts to reveal the core or the surrounding area of the galaxy. The largest of the three images is the full extent of our image. The 20″ tick marks correspond to 9.7 kpc at a distance of 100 Mpc for the system. Figure 2 (Plate 4) is our *R* image, again displayed with varying contrast to enhance the core or the surrounding area. Figure 3 (Plate 5) is an image of the *R* data divided by the *U* data, so that redder emission appears darker. An inset to the figure shows the galaxy core on the same linear scale. Contour maps of all three of the images are presented in Figures 4, 5, and 6. Photometry through a series of mathematical apertures is presented in Table 2. These data are discussed in detail in § III*a*.

b) Near-Infrared Observations

Near-infrared images of NGC 6240 were obtained using the Astrophysical Research Consortium (ARC) prototype HgCdTe array camera (Hereld, Harper, and Pernic 1990) at the Cassegrain foci of the Wyoming Infrared Observatory (WIRO) 2.3 m and the University of California 3.1 m Shane telescopes. Observations of the galaxy in the *H* (1.6 μm) band were obtained in Wyoming during 1988 June, while the *J* (1.25 μm) and *K* (2.2 μm) images were obtained at the Lick Observatory telescope during 1988 August. Observations at higher angular resolution at *H* were obtained at Lick Observatory in 1989 May. The WIRO observations were obtained under conditions of good seeing, but only mediocre transparency. The California observations were made under good conditions.

The camera was configured to give a scale of 0″.68 pixel^{-1} for the *J* amd *K* observations in California, 0″.61 pixel^{-1} for the Wyoming *H* observations, and 0″.24 pixel^{-1} for the higher resolution *H* observations in California. With the seeing, the average angular resolution is about 1″ for the *H* observations from California and about 1″.5 for the other bands. The total field of view of the array was about 42″ × 42″ (20.2 kpc on a side). Exposure times were chosen so that the sky background was about half–full-well potential to ensure that object photons occupied the linear regime of the detector. Total net on-source integration times were 280 s for the *J* and 350 s for the *K* images from Lick Observatory, 480 s for the *H* images from Lick Observatory, and about 1000 s for the WIRO *H* image.

We processed the images by first subtracting an appropriate

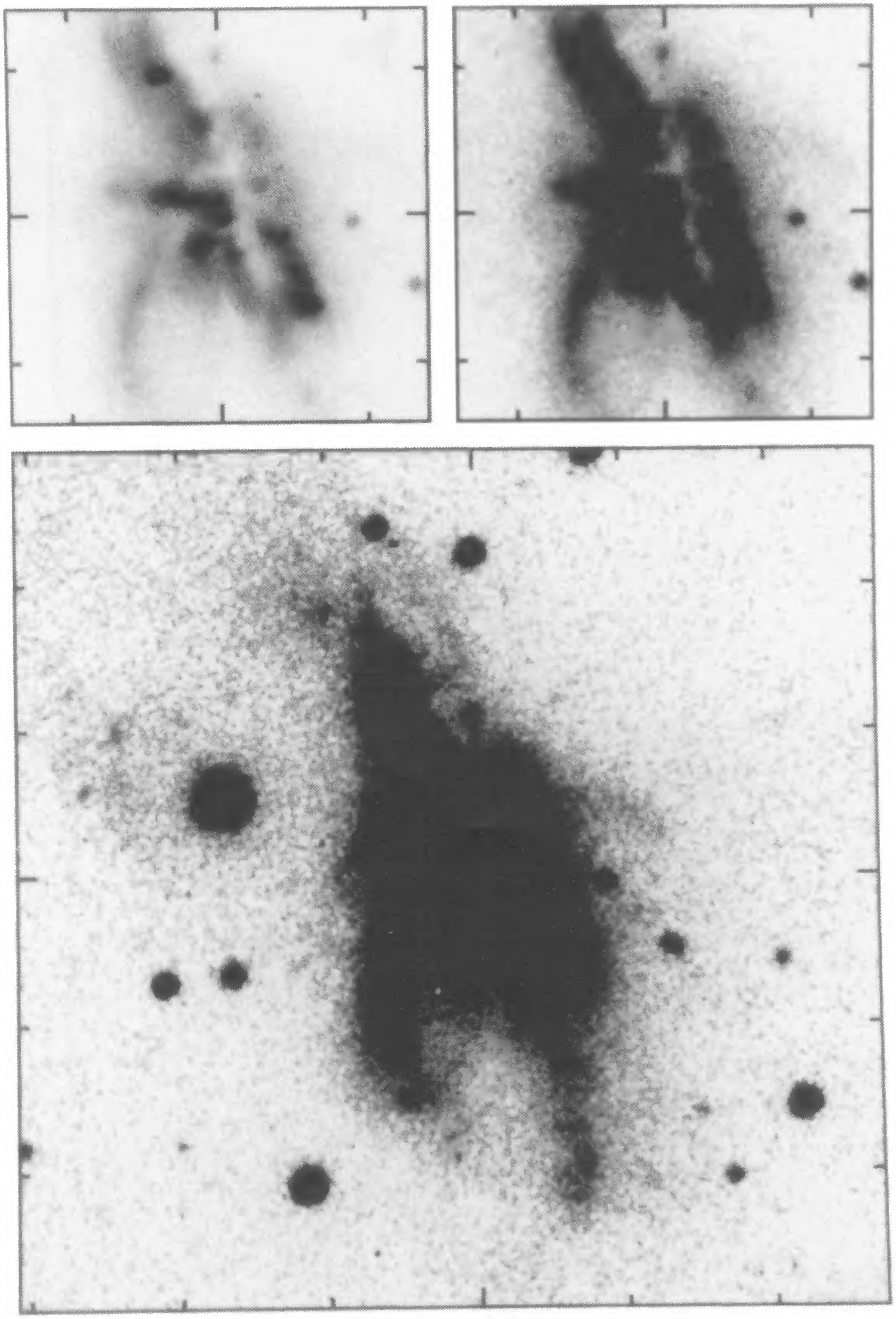

FIG. 1.—Image of NGC 6240 at U (0.36 μm) shown at different zero points and maximum intensities to reveal the source structure in different parts of the object. All the images are on the same scale, with the tick marks separated by 20″ (9.7 kpc at a distance of 100 Mpc). The bottom image is the full frame. The scaling of the intensity is linear in all images. North is up, and east is to the left.

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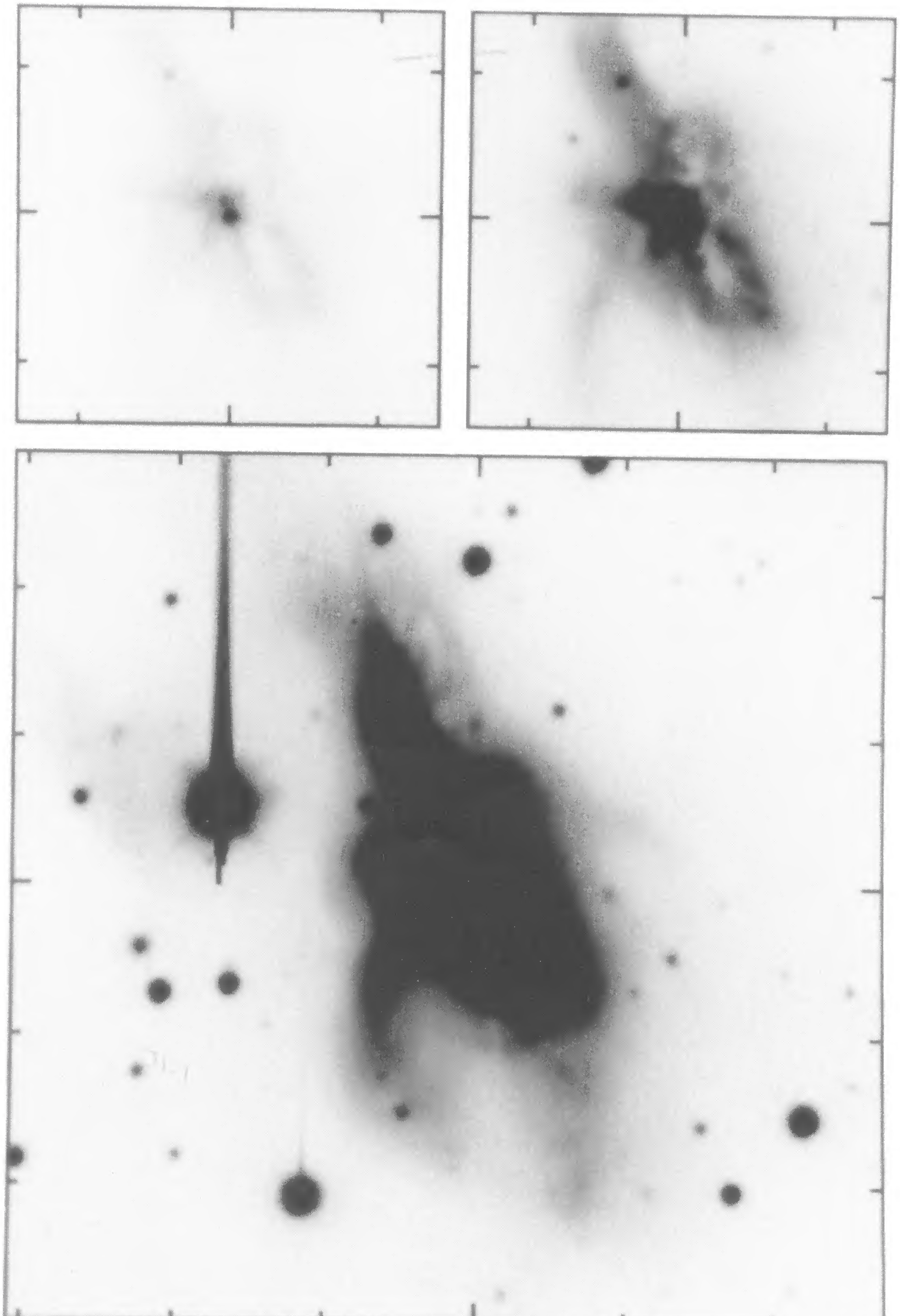

FIG. 2.—Image of NGC 6240 at R (0.65 μm) shown at different zero points and maximum intensities to reveal the source structure in different parts of the object. All the images are on the same scale, with the tick marks separated by 20″ (9.7 kpc at 100 Mpc). The bottom image is the full frame. The scaling of the intensity is linear in all images. North is up, and east is to the left.

THRONSON *et al.* (*see* **364**, 458)

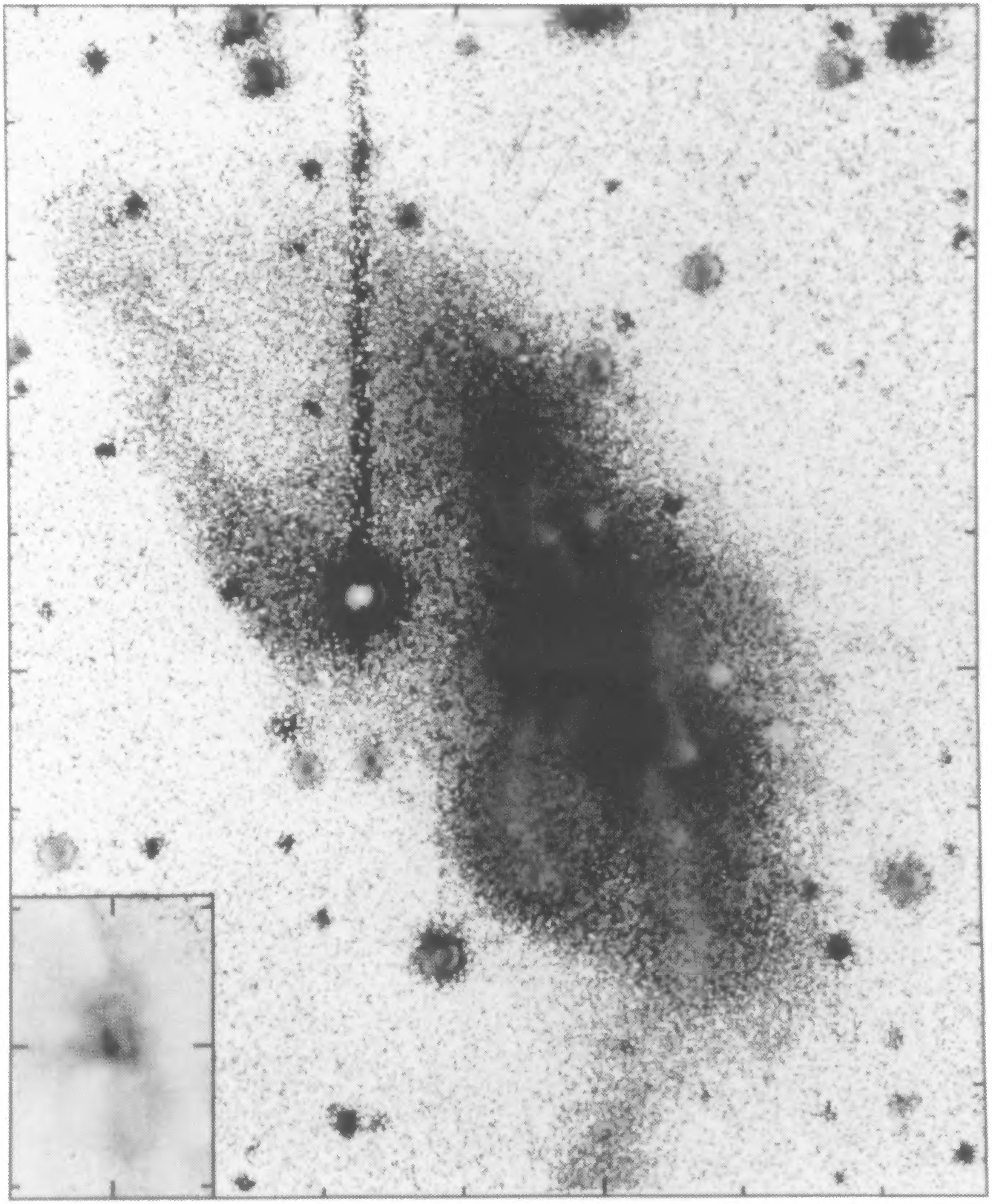

FIG. 3.—Image of the *R* intensity divided by the *U* intensity, so that the redder emission appears darker. The inset shows the inner ~40″ core of the galaxy, roughly the same region as that covered by our near-infrared images. Both images are on the same scale, with tick marks separated by 20″ (9.7 kpc at a distance of 100 Mpc). North is up, and east is to the left.

THRONSON *et al.* (*see* **364**, 458)

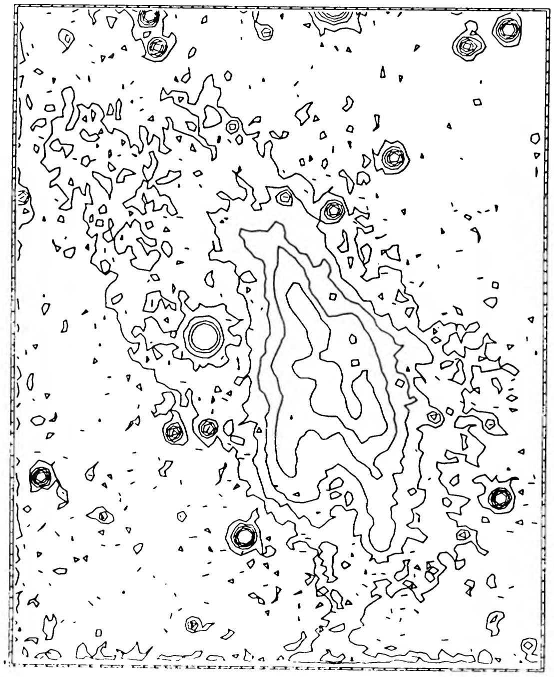

FIG. 4a

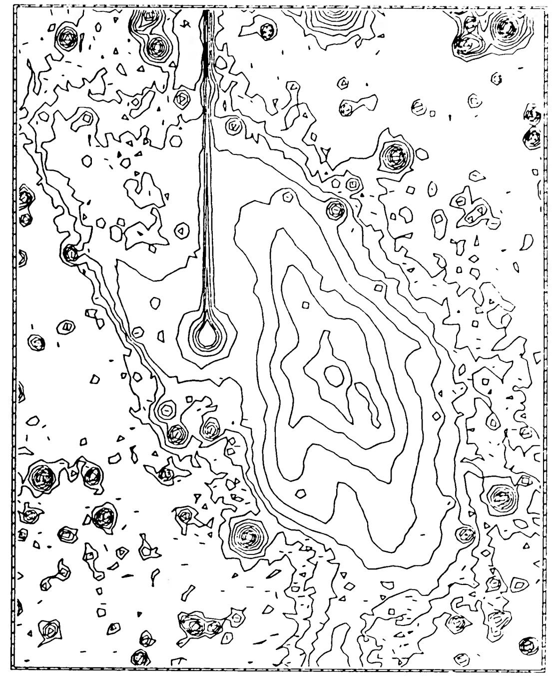

FIG. 4b

FIG. 4.—(a) Contours of our full U (0.36 μm) frame. The separation of levels is 1 mag arcsec^{-2}, beginning with 25.86 mag arcsec^{-2}, with the highest contour drawn at 21.86 mag arcsec^{-2}. (b) Same as for (a), but for our R (0.65 μm) image, with the lowest contour drawn at 26.90 mag arcsec^{-2} and the highest contour at 18.90 mag arcsec^{-2}. In both figures, north is up, east is to the left, and the figure dimension is 174″ × 139″ (north-south × east-west) or 84.5 kpc × 67.5 kpc at a distance of 100 Mpc.

frame of blank sky, which, in most cases, was the weighted average of several sky exposures taken close in time to the object image. This average is intended to be most representative of the conditions during the period when the galaxy was observed, while at the same time reducing the contribution of the sky subtraction to the noise in our final image. This procedure also corrects for dark current and zero-point offset. Following this, we divided the images by a normalized flat-field frame to remove nonuniform pixel-to-pixel efficiencies in the array. Photometry of the images through a series of numerical apertures is presented in Table 2. Our near-infrared images are presented in Figure 7 (Plate 6), all but one presented with the same linear scale. Contour maps of our near-infrared data are presented in Figures 5 and 6.

In general, there is satisfactory agreement with the earlier photometry of this source in the near-infrared by Rieke *et al.* (1985). Disagreement for observations with small apertures (less than about 4″) may be explained by the differences in

TABLE 2

VISUAL AND NEAR-INFRARED PHOTOMETRY
(in magnitudes)

APERTURE DIAMETER (arcsec)	U (0.36 μm)		R (0.65 μm)		J (1.25 μm)		H[a] (1.65 μm)		K (2.2 μm)	
	N	S	N	S	N	S	N	S	N	S
1[b]	21.12	21.01	18.25	17.74	15.55	14.85	13.94	12.91	13.59	12.54
2	19.76	19.67	16.93	16.49	14.20	13.54	12.82	12.04	12.36	11.54
3	18.95	18.89	16.18	15.88	13.43	12.99	12.18	11.70	11.67	11.14
4	18.39	18.37	15.63	15.48	12.90	12.64	11.62	11.46	11.14	10.89
8.5	...	17.01	...	14.48	...	11.90	...	11.00	...	10.40
30	...	14.76	...	12.96	...	11.03	...	10.28	...	9.77
Total	...	13.7	...	12.23	...	...	...	...	...	...
Estimated absolute[c]	...	−24.5	...	−24.2	...	−25.3	...	−25.8	...	−26.1
Estimated absolute[d]	...	−22.5	...	−23.4	...	−25.0	...	−25.6	...	−26.1

NOTE.—Estimated uncertainty for measured magnitudes ±0.05 mag, except for total U-magnitude, for which we estimate ±0.2 mag. The uncertainties in our absolute magnitudes (adopted distance of 100 Mpc) are probably about ±0.3 mag, primarily the difficulty of scaling incomplete maps to the total area of the galaxy. "N" refers to photometry centered on the north nucleus, and "S" refers to photometry centered on the south nucleus.

[a] Photometry for apertures of 1″–4″ taken from higher resolution Lick Observatory data. Larger aperture photometry taken from WIRO data.

[b] Included for completeness: visual seeing about 1″–1″.5.

[c] Assuming $I_\lambda = I_{\lambda,0} \exp(-\tau_\lambda)$, with $\tau_V = 1.8$ ($A_V = 2$).

[d] Assuming $I_\lambda = I_{\lambda,0}[1 - \exp(-\tau_\lambda)]/\tau_\lambda$, with $\tau_V = 1.8$ ($A_V = 2$).

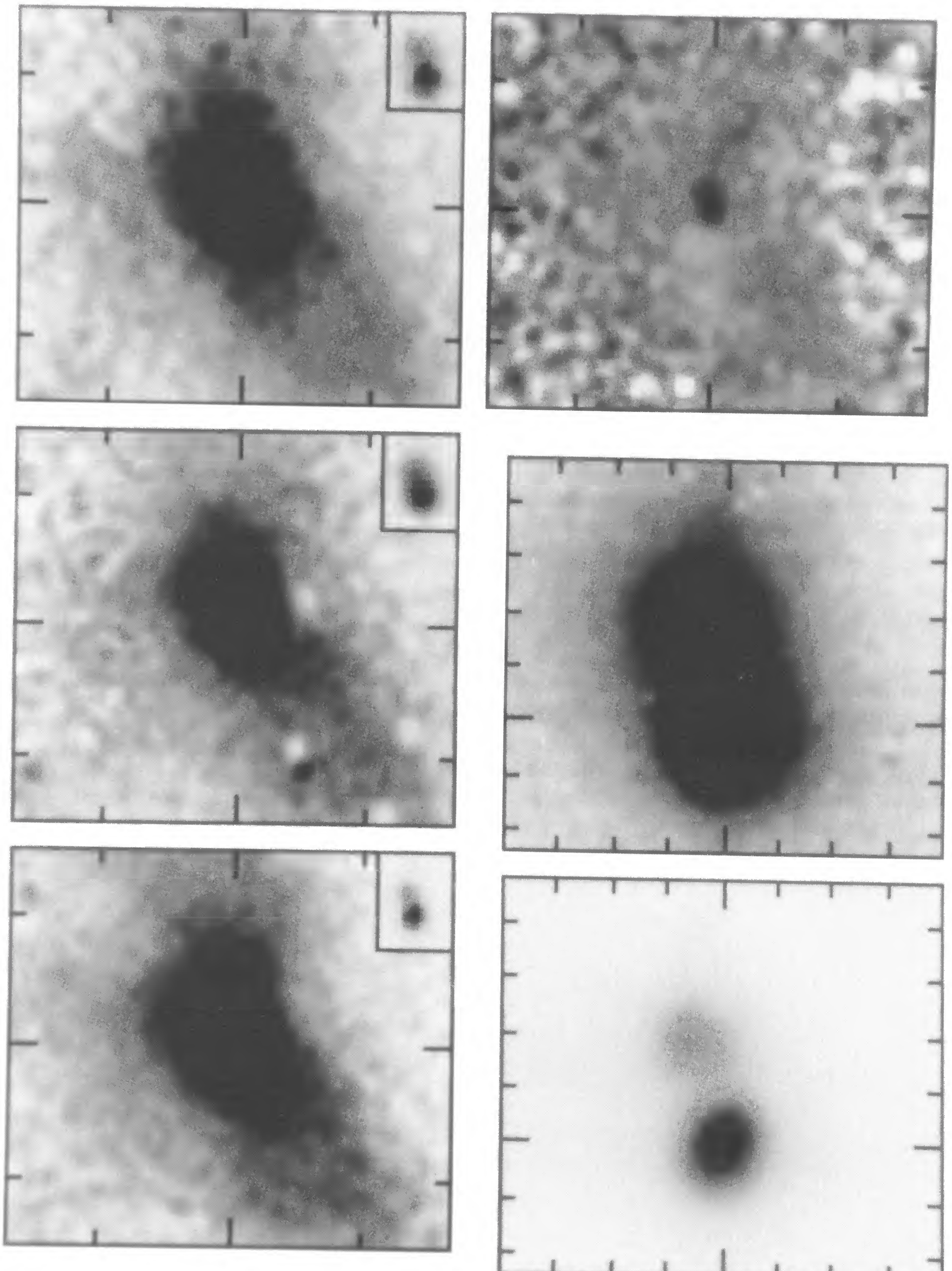

FIG. 7.—Our near-infrared images of NGC 6240 on a linear intensity scale. The three on the left side are, from top to bottom, J (1.25 μm), H (1.65 μm), and K (2.2 μm), while the upper right-hand image is the J intensity divided by the K intensity, with the redder color appearing darker. Insets show the core of the galaxy system on the same scale. These four images have tick marks that are separated by 10″ (4.9 kpc at a distance of 100 Mpc). The two images at the lower right are our high-resolution H (1.65 μm) data, also on a linear intensity scale, with the tick marks separated by 1″ (490 pc at a distance of 100 Mpc). North is up, and east is to the left.

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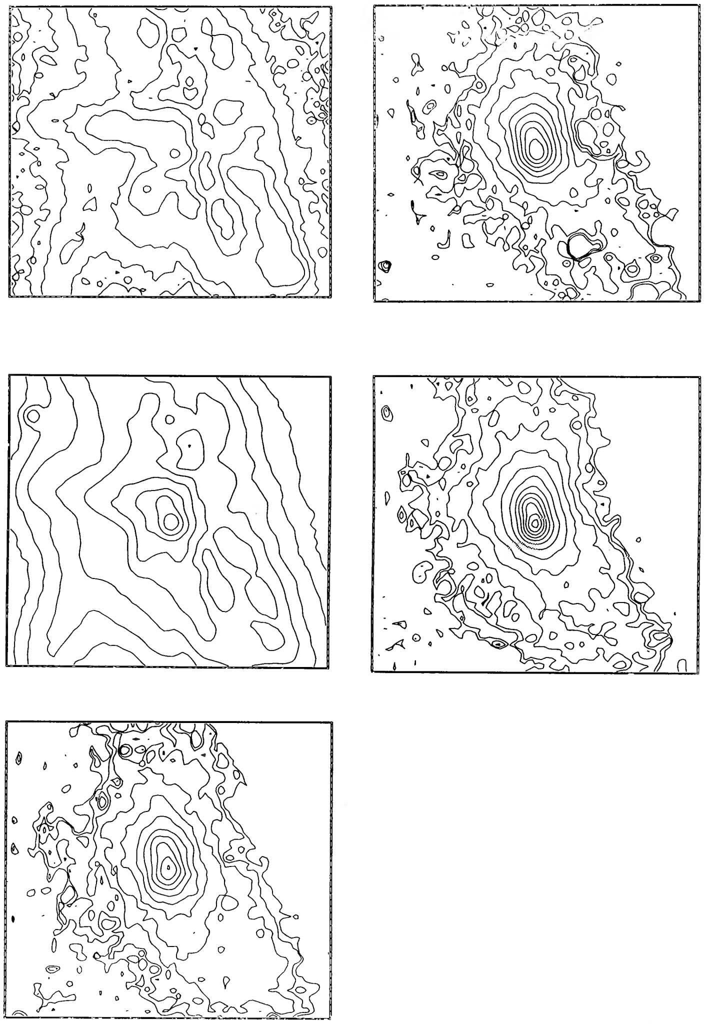

FIG. 5.—Contour maps of our images of NGC 6240 that cover 33″.6 × 30″.2 (east-west × north-south) in five bands, or an area of 16.3 kpc × 14.7 kpc at a distance of 100 Mpc. All levels are separated by steps of 0.5 mag arcsec^{-2}. In all cases, north is up and east is to the left. The sequence of panels runs from (*a*) at the upper left through (*c*) at the lower left, and (*d*) is above (*e*) on the right. (*a*) *U* (0.36 μm) with lowest contour equal to 23.86 mag arcsec^{-2} and highest equal to 20.86 mag arcsec^{-2}. (*b*) *R* (0.65 μm) with lowest contour equal to 21.90 mag arcsec^{-2} and highest equal to 17.90 mag arcsec^{-2}. (*c*) *J* (1.25 μm) with lowest contour equal to 19.65 mag arcsec^{-2} and highest equal to 14.65 mag arcsec^{-2}. (*d*) *H* (1.65 μm) with lowest contour equal to 18.55 mag arcsec^{-2} and highest equal to 14.05 mag arcsec^{-2}. (*e*) *K* (2.2 μm) with lowest contour equal to 18.67 mag arcsec^{-2} and highest equal to 12.67 mag arcsec^{-2}.

placement of our computer apertures and the uncertainty in positioning of the telescope by Rieke *et al.* for this object with a pair of bright nuclei separated by only about 2″.

III. ANALYSIS AND DISCUSSION

a) General Description of Images and Photometry

Our *U* image (Fig. 1) and, to a lesser degree, the *R* image (Fig. 2) clearly show the great wisps, tails, and streamers that are characteristic of an advanced merger. Other revealing visual images have been presented by Fried and Schulz (1983), Armus, Heckman, and Miley (1987), and Keel (1990). Recently, Keel (1989) produced a true-color image of NGC 6240. This is an extraordinarily disrupted system, and it is not at all difficult to imagine the torture that the ISM is undergoing as a pair of gas-rich galaxies collide at high velocity. We also note, in particular, the lumpy and knotty appearance of the system, particularly at the shortest wavelength, which suggests that young, very blue stars are visible throughout the object. Star formation, if it is the source of both the broad-band UV emission (Fig. 1) and the extended Hα emission, appears to be taking place over a large area within the galaxy. Whether young stars are forming as a direct result of the merger and what their relative contribution is to the total luminosity of NGC 6240 are, of course, primary questions in our paper.

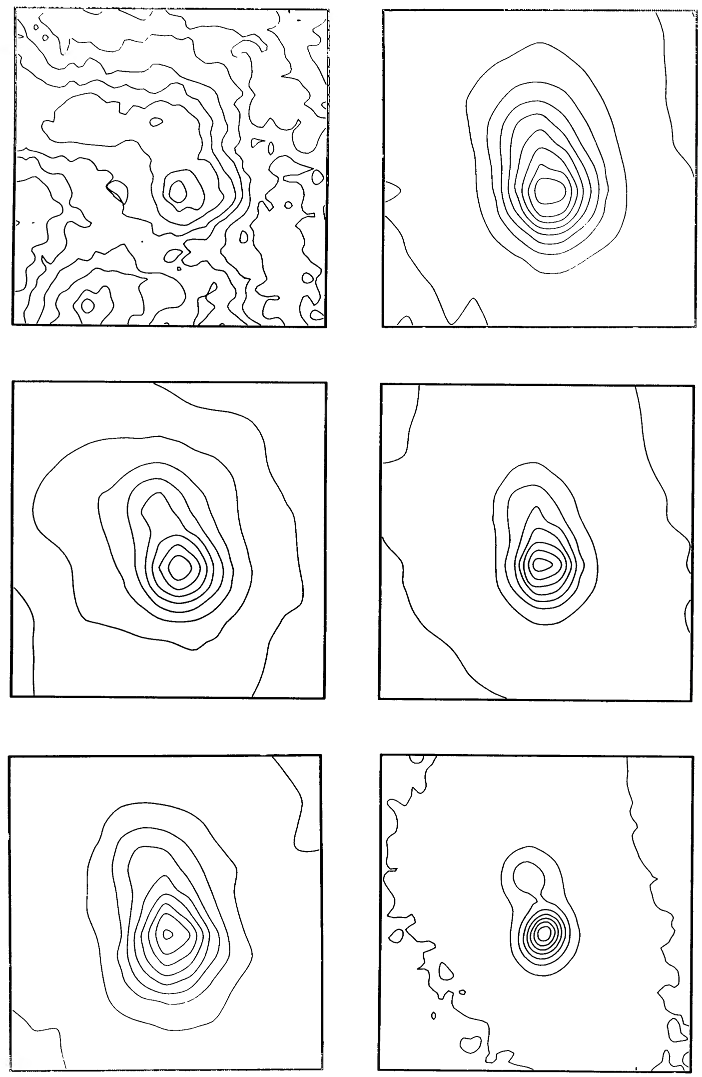

FIG. 6.—Contour maps of our images of NGC 6240 that cover 9″.9 × 9″.9 (4.8 kpc at a distance of 100 Mpc) in five bands with linear scaling of the intensity. In all cases, north is up and east is to the left. The sequence of panels runs from (*a*) at the upper left through to (*c*) in the lower left, and from (*d*) at the upper right through to (*f*) at the lower right. (*a*) *U* (0.36 μm) with the highest contour at 20.75 mag arcsec^{-2} and each step equal to 0.125 of the peak intensity. (*b*) *R* (0.65 μm) with the highest contour at 17.40 mag arcsec^{-2} and each step equal to 0.1 of the peak. (*c*) *J* (1.25 μm) with the highest contour equal to 14.66 mag arcsec^{-2} and each step equal to 0.125 of the peak. (*d*) *H* (1.65 μm) with the highest contour equal to 13.75 mag arcsec^{-2} and each step equal to 0.12 of the peak. (*e*) *K* (2.2 μm) with the highest contour equal to 12.54 mag arcsec^{-2} and each step equal to 0.14 of the peak. (*f*) Our high-resolution *H* (1.65 μm) contour map, with the highest contour equal to 12.55 mag arcsec^{-2} and each step equal to 0.14 of the peak.

Of the two visual images, the nuclei are more evident at R, a wavelength that should penetrate interstellar dust somewhat, as well as reveal the cooler, older stellar population in the former bulges of the precursors to NGC 6240. Moreover, the distribution of the light appears smoother and less knotty than is the case at U. This is a qualitative impression, but a notion which agrees with our expectation that the red light should be sensitive to the widely distributed red giant and low-mass dwarf population. Our near-infrared images (below) show a similar structure. Our U and R band two-color image (Fig. 3) shows that NGC 6240 is a red object over much of its area (see also our Table 2), consistent with a disrupted and dispersed dusty ISM. The galaxy core (Fig. 3, *inset*) shows the two nuclei, very much redder than their surroundings. The brighter southern source is an active nucleus, which DePoy, Becklin, and Wynn-Williams (1986) argued was the major contributor to the energetics of the galaxy, a proposal which conflicts with most other work on this object.

Twisting through the extended red light are arcs of bluer emission (large section of Fig. 3), which may be regions of enhanced star formation or portions of the galaxy which are less heavily extinguished. We favor the former interpretation, since the bluer regions of extended emission are distributed somewhat similarly to the Hα emission mapped by Armus, Heckman, and Miley (1987). These bluer filaments can be easily traced in Fig. 3 over distances equivalent to 10–20 kpc, although they appear to be only ~ 2 kpc wide. We surmise that these elongated blue structures are the remnants of the spiral structure in the precursors (assuming that the gas-rich galaxies that collided were once spirals) within which the interstellar gas was concentrated. Consequently, although the galaxy as a whole appears badly disrupted, the location of star formation—or at least of the blue stellar population—is not entirely randomized but has retained a significant amount of its past large-scale coherence.

Our near-infrared images (Fig. 7) appear very different from our visual images, which is due in large part to the greater penetration of the dust by near-infrared photons and the different stellar population that contributes the bulk of the light at this wavelength. The gross brightness distributions at all three wavelengths are very similar, with the pair of nuclei distinct and an elongated "halo" of lower brightness emission surrounding both. Without additional information, we take the H image as best representing the distribution of the red giants and supergiants, as well as the low-mass dwarfs that make up the majority of the luminous matter in galaxies. Light at J can be sufficiently contaminated by small numbers of hot young stars that the brightness distribution may be ambiguous (Telesco, Decher, and Gatley 1985; Thronson and Greenhouse 1988). Similarly, at K, there can be an important contribution from dust at a few hundred degrees, perhaps associated with active star formation in the source. However, the upper right-hand image in Figure 7 shows our $J-K$ image, which shows constant color over the region imaged, with the exception of the very red southern nucleus. We interpret this as indicating that both J and K are dominated by the same galaxian component, the late-type stellar population, with the exception of the nucleus. Because we found no clear bright knots or non-nuclear point sources over the 30″ diameter region that we mapped in the near-infrared, we are able to estimate an upper limit to the supernova rate (§ III*c*).

Our high-resolution H image (Fig. 7, *lower right-hand image*) shows the pair of nuclei separated by 1″85 at a position angle of 19°2 ± 0°4. The location and brightness distribution are consistent with those reported by Rieke (1987).

Although the following sections are devoted to a quantitative discussion of NGC 6240, we can use our multiaperture photometric data (Table 2) to reveal qualitatively some aspects of this system. The following discussion is consistent with the more detailed results in §§ III*b* and III*c*. For models of broad-band galaxian colors as a function of such processes as dust absorption or emission, and active star formation, we shall use the results of Thuan (1985) and Telesco, Decher, and Gatley (1985, especially Fig. 5). In particular, we find that the $J-H$ and $H-K$ colors of the galaxy in the largest aperture for which we have data (30″) are typical of those found for normal galaxies, modified by a 10%–20% enhancement of the K flux, perhaps from hot dust. Presumably these grains are associated with the energetic star formation that is taking place throughout the object (§ III*c*), although there is enough scatter in the observations of normal galaxy to make the $H-K$ colors ambiguous to relative contributions by warm dust of less than about 10%.

As the aperture size decreases, the measured $H-K$ color reddens by 0.05–0.1 mag, but the $J-H$ color reddens by 0.6 mag. A simple explanation is increasing extinction, which affects the shorter wavelength bands more than K. The colors in the 4″ aperture, for example, are consistent with $A_V = 4$–5 mag, along with a small (about 10% and perhaps less) contribution from hot dust to the K emission. This increase in the extinction in small apertures confirms the large obscuration found earlier for the nuclei (e.g., Rieke *et al.* 1985; Smith, Aitken, and Roche 1989), but with only modest absorption over most of the source (see § III*b*).

b) Estimating the Stellar Luminosity of NGC 6240 and Other Galaxies

In addition to a morphology that demonstrates that the galaxy is almost certainly the consequence of a merger (see § I), the characteristic that has attracted most attention to NGC 6240 is its relatively large far-infrared luminosity. Using $L_{IR}(L_\odot) = 5.6 \times 10^5 D^2(\mathrm{Mpc})[2.58 F_{60}(\mathrm{Jy}) + F_{100}(\mathrm{Jy})]$ to estimate the far-infrared luminosity from 60 and 100 μm data from the *Infrared Astronomical Satellite* (*IRAS*) data (Lonsdale *et al.* 1985), we find $L_{IR} = 4.8 \times 10^{11}\ L_\odot$ at 100 Mpc ($1\ L_\odot \equiv 3.85 \times 10^{33}$ ergs s^{-1}), over the large (few arcmin) *IRAS* beams ($1' = 29$ kpc at the distance that we adopt for the galaxy). This derived value applies to the wavelength range 40–120 μm and there is likely to be modest (about 30%) additional flux outside this band. The far-infrared luminosity is substantially in excess of the stellar emission observed at visual and near-infrared wavelengths, a result which has aroused numerous investigators. Moreover, this infrared luminosity exceeds the energy emitted by nonmerging galaxies over the same wavelength range. For example, Rice *et al.* (1988) derived far-infrared luminosities for a large number of nearby galaxies. Typical values for luminous spirals (e.g., NGC 891, NGC 1365, NGC 7331, M51, and M83) are in the range $L_{IR} = (0.5$–$2) \times 10^{11}\ L_\odot$, less than that found for NGC 6240, although only by small factors in some cases. The Milky Way, a modest spiral, has $L_{IR} \approx 0.15 \times 10^{11}\ L_\odot$ (Cox and Mezger 1989).

However, as Lester, Harvey, and Carr (1988) point out, the stellar *bolometric* luminosity of the merging galaxy NGC 6240 is not much different from that for a typical *pair* of luminous spiral galaxies. In § IV we estimate stellar luminosities for a large number of normal isolated galaxies, and we find that total luminosities of average to very large spirals are commonly in the range of 10^{10} to a few times 10^{11} $L_{\odot}$. A pair of such very luminous spirals can approach 10^{12} $L_{\odot}$, exceeding the total observed for NGC 6240 and many other apparent merging systems. The sobriquet "ultraluminous," therefore, is excessive when applied to objects such as NGC 6240 with total luminosities of a few times 10^{11} $L_{\odot}$.

We now demonstrate that visual light from the older stellar population, if the dust is sufficiently thick and widespread to intercept the bulk of the radiation field, can easily make a major contribution to the far-infrared luminosity. Figure 8 shows the energy distributions for some of the models of Arimoto and Yoshii (1986), who calculated the colors of galaxies for a variety of star-forming histories. For clarity, only three curves are shown in the figure. The center curve is a "typical" spiral galaxy, the model proposed for the Milky Way by Arimoto and Yoshii. A pair of extrema is also shown, which correspond approximately to an elliptical and to a star-forming irregular. The curves are normalized to the same flux density at I (0.9 μm), which is close to the wavelength of maximum energy emission. We have plotted νF_{ν} $(=\lambda F_{\lambda})$ against log λ, since equal areas in this type of graph have equal integrated flux. Thus, for example, we see that for many galaxies, approximately equal amounts of energy are emitted at wavelengths shortward and longward of 1 μm. Figure 8 also includes the total spectral energy distribution of NGC 6240, corrected for extinction under two different assumptions about the relative location of stars and dust in the system, which we now discuss.

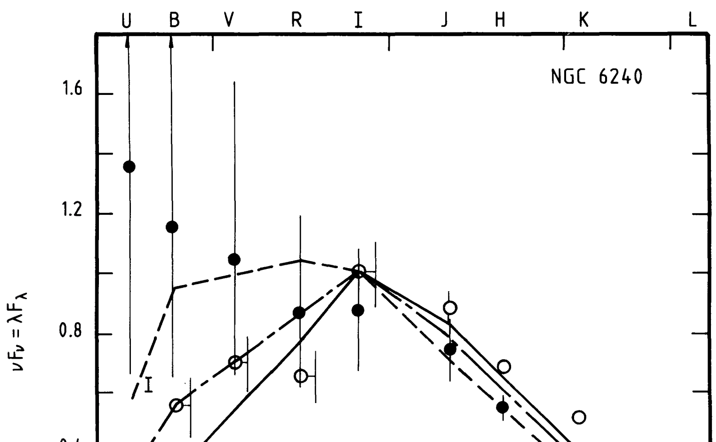

FIG. 8.—Calculated intrinsic colors for galaxies are extremely sensitive to the assumed dust distribution, even for modest obscuration. Spectral energy distribution of NGC 6240, corrected for an extinction of $A_V = 2$ mag as described in § III*b* (see also the Appendix), superposed on the models for galaxy evolution by Arimoto and Yoshii (1986). Filled circles are the corrected fluxes for an assumed overlying screen, while the open circles are for the uniform dust/stars mixture. Error bars are equivalent to an uncertainty in the extinction of $A_V = \pm 0.5$ mag in both cases. Equal areas under the curve in this plot of λF_{λ} vs. log λ are proportional to equal flux. The three different distributions represent a very active star-forming galaxy, such as a Magellanic irregular; a more subdued star-forming system, such as a normal spiral; and a galaxy within which star formation has nearly ceased, such as an elliptical; these are designated I, S, and E, respectively. The model curves have all been normalized to a value of unity at the I band.

There is a great deal of photometry available for this object, but we must correct for significant dust extinction, which previous authors assumed was distributed in a simple overlying screen with observed intensity varying as $I_{\lambda} = I_{\lambda,0} \exp(-\tau_{\lambda})$. Fried and Schulz (1983) estimated $A_V = 1$ mag from dust in the Milky Way and obscuring the larger part of the galaxy, but $A_V = 3$ mag within the luminous region immediately surrounding the double nuclei within NGC 6240. Estimates within about 1 mag of this were derived by Fosbury and Wall (1979), DePoy, Becklin, and Wynn-Williams (1986), and Lester, Harvey, and Carr (1988). Rieke *et al.* (1985), on the other hand, derived a much larger value, $A_V \approx 15$, from their mid-infrared observations, which DePoy, Becklin, and Wynn-Williams argued applies only to the immediate vicinity of the dusty nuclei. Smith, Aitken, and Roche (1989) also estimated very large visual extinctions in the several arcsecond core. We are more concerned with the large-area emission and, under the assumption of an overlying dusty screen, adopt $A_V = 4$ mag as the total extinction to the luminous central regions of NGC 6240, but $A_V = 1$ for the extended regions that emit much of the visual and near-infrared light. For a single value for the extinction that will allow us to estimate corrected absolute magnitudes, we adopt an average for the range of values over the entire source, $A_V = 2$ mag.

Table 2 lists our observed magnitudes and the area over which they apply. To correct for extinction as a function of wavelength, we adopt $A_V = 0.63A_U = 0.8A_B = 1.4A_R = 2.1A_I = 3.6A_J = 5.8A_H = 11A_K$ (Draine 1989), with $A_V = 2$ mag. We follow current convention and first blissfully ignore the important question as to whether or not the "uniform screen" model is the proper choice to approximate the dust distribution in NGC 6240 or in many other galaxies. It probably is not, as Bruzual, Magris, and Calvet (1988) and Disney, Davies, and Phillipps (1989) discuss in detail. If the extinction is small, the adopted model is relatively unimportant, but this is not the case here. In our appendix, we justify one simple alternative to the screen model: a uniform distribution of stars and dust, which gives $I_{\lambda} = I_{\lambda,0}[1 - \exp(-\tau_{\lambda})]/\tau_{\lambda}$. This simple alternative produces calculated intrinsic galaxian colors that are very different from those under the assumption of an overlying screen, even for very modest total dust optical depths.

From the largest apertures for which photometry is available, we use $m_U = 13.7$ (total; Table 2), $m_B = 13.98$ (62″; Fosbury and Wall 1979), $m_V = 13.17$ (62″; Fosbury and Wall 1979), $m_R = 12.2$ (total; Table 2), $m_I = 11.4$ (70″ × 41″; Fried and Schulz 1983), $m_J = 11.0$ (30″; Table 2), $m_H = 10.3$ (30″; Table 2), and $m_K = 9.8$ (30″; Table 2). We can correct all photometry to emission from the entire galaxy by assuming that the stellar brightness distribution at all wavelengths is the same as that for our R image. For a distance of 100 Mpc and a uniform screen with $A_V = 2$ mag, the absolute magnitudes corrected for extinction become $M_U \approx -24.5$, $M_B \approx -23.6$, $M_V \approx -23.9$, $M_R \approx -24.2$, $M_I \approx -24.7$, $M_J \approx -25.3$, $M_H \approx -25.8$, and $M_K \approx -26.1$. This spectrum is plotted as the filled circles in Figure 8, normalized by eye so that the points at wavelengths longward of R approximately fit that of the model spiral galaxy, presumably the precursor to NGC 6240. Note that, regardless of this normalization, correction of the observed colors via a simple screen model produces an extremely blue spectrum, with relative emission at short wavelengths in excess of that found for even very energetic, gas-rich irregulars. Very suspicious. Notice also, however, that this extraordinarily blue emission contributes only about one-third of the total intrinsic stellar flux in NGC 6240, at least over the wavelengths that have been observed.

Assumption of a screen of obscuring dust is incorrect for galaxies and leads to significant errors in, for example, derived intrinsic visual colors. With visual extinctions in excess of 0.5 mag in NGC 6240 and, probably, many normal disk galaxies (Bruzual, Magris, and Calvet 1988; Disney, Davies, and Phillipps 1989), an alternative approximation to the dust/star distribution must be adopted. Our approximate alternative is described in the Appendix, and the result is shown as the open circles in Figure 8, where we normalized the deduce I flux to unity. For this demonstration, we adopted $A_V = 2$ mag, which gives monochromatic absolute magnitudes of $M_U \approx -22.5$, $M_B \approx -22.3$, $M_V \approx -23.0$, $M_R \approx -23.4$, $M_I \approx -24.4$, $M_J \approx -25.0$, $M_H \approx -25.6$, and $M_K \approx -26.1$.

Direct integration of the derived energy distribution gives a stellar (0.36–3 μm) luminosity of $L_* \approx 2.5 \times 10^{11}$ $L_\odot$ for obscuration in the form of a screen and 1.8×10^{11} $L_\odot$ for the dust/stars mixture. These values are in the range typical for a pair of luminous spirals. Thus, the luminosity of the stars is between one-fourth and one-half that of the observed infrared dust emission. Although the derived intrinsic colors of the galaxy depend sensitively upon the model adopted for the dust distribution (Fig. 8; our appendix), the total calculated stellar luminosity is less uncertain, since a large fraction of the flux is emitted at longer wavelengths, where the effects of extinction are reduced. An uncertainty in the adopted extinction of ± 0.5 mag at V translates into an uncertainty of about $\pm 25\%$ in the derived luminosity for the screen model and about $\pm 10\%$ for the mixture model. If the average photon suffers 2 mag of extinction at V, then almost all the stellar luminosity will be converted into infrared emission from the interstellar dust, and the stellar light will make a major contribution toward heating the dust. Given the large uncertainties in adopted extinction models, plus the small contribution from blue stars as demonstrated by the open circles in Figure 8, we argue that the older stellar population is likely to be the largest single contributor toward heating the dust in NGC 6240.

Much of the U and B band flux arises from young stars. We make the approximation that all the light emitted shortward of 0.6 μm in Figure 8 is produced by the youngest stellar population, giving $L_{*,\,\mathrm{young}} \approx (0.3\text{–}1) \times 10^{11}$ $L_\odot$, depending upon the extinction model adopted, or less than one-third of the total stellar light. This does not include emission at wavelengths below the atmospheric cutoff at about 0.34 μm. We shall estimate in § IIIc that the luminosity of the stars that are ionizing the ISM in this galaxy is close to the value that we calculate here from the U and B photometry. Regardless of which of the pair of possible extinction models is used, our multiband photometry does not support the hypothesis of a population of young stars sufficient in luminosity to dominate the dust heating.

We may use the model galaxian spectra of Arimoto and Yoshii (1986; our Fig. 8) for an alternative estimate of the stellar luminosity that is less susceptible to extinction problems. In Table 3 we compile conversions from absolute magnitude to stellar bolometric magnitude for the range of models produced by Arimoto and Yoshii. The table also includes an uncertainty that represents the full range of derived galaxy models. This is, therefore, a measure of how accurately the

TABLE 3

DERIVED CONVERSIONS BETWEEN BOLOMETRIC AND ABSOLUTE MAGNITUDES

M	M_{bol}	M	M_{bol}	M	M_{bol}
M_U.....	-1.2 ± 0.8	M_R.....	$+0.3 \pm 0.2$	M_H.....	$+1.8 \pm 0.3$
M_B.....	-1.2 ± 0.5	M_I.....	$+0.8 \pm 0.1$	M_K.....	$+2.3 \pm 0.4$
M_V.....	-0.5 ± 0.2	M_J.....	$+1.4 \pm 0.3$	M_L.....	$+2.5 \pm 0.5$

NOTE.—Emission from stellar photospheres only. Uncertainty is a generous estimate for the full range for all normal galaxy types adapted from the models of composite systems of stellar evolution of Arimoto and Yoshii 1986.

stellar luminosity can be derived when almost nothing is known *a priori* about star formation activity and the history of the source. Table 3 gives a very narrow range of estimated bolometric magnitudes for the four bands that are likely to be the most reliable in estimating the stellar luminosity, R, I, J, and H. We consider it possible that the K-band emission is contaminated by hot dust. Although the results in Table 3 indicate that the I-band magnitude has the smallest formal uncertainty, the effect of the poorly understood obscuration is large at this wavelength. For that reason, we adopt a simple average of the four values for bolometric magnitude and find $M_{\mathrm{bol}} \approx -23.9$ for a screen of dust and -23.5 for the mixture. These values may be compared with $M_{\mathrm{bol}} = -21.7$ for the Milky Way. If $M_{\mathrm{bol},\odot} = 4.75$, then the luminosity of a nearly normal mixture of stars in NGC 6240 is $L_* \approx (2\text{–}3) \times 10^{11}$ $L_\odot$, in agreement with our direct integration above.

If, as we suggest, old stars make a major contribution to heating of the dusty ISM, then the far-infared emission should roughly follow the distribution of the stellar light. However, star formation and, perhaps, some kind of active nucleus each contribute about 25% to the total energetics (§ IIIc), and these components are distributed differently from the stars. Because the dust warmed by the older stars is likely to be more diffuse than the material close about young stars, we expect that it will be the cooler material, in emission around 100 μm, that will more closely follow the stellar light (see the model for the dust emission from NGC 6240 by Draine 1990).

c) Star Formation and the ISM in NGC 6240

One conclusion is clear: a "superburst" of star formation directly related to the merger may not be necessary to explain alone the large far-infrared luminosity from NGC 6240. Moreover, since the object is—or once was—a pair of gas-rich galaxies, it is reasonable to expect continuing star formation at some level despite the galaxy collision. In this section, we attempt to estimate the total rate of star formation in NGC 6240. We also discuss evidence that the young stars in this object formed entirely independently of the merger, an argument which is based on our estimate that the efficiency of star formation is in the range derived for normal galaxies, although with considerable uncertainties. We shall also comment on the mass of the interstellar medium within the system and the lifetime of stellar formation.

Heckman, Armus, and Miley (1987) found the Hα flux from this galaxy over $\sim 3'$, $F_{\mathrm{H}\alpha} = 1.5 \times 10^{-12}$ ergs cm^{-2} s^{-1} or $L_{\mathrm{H}\alpha} = 4.7 \times 10^8$ $L_\odot$, uncorrected for extinction. If this visual line flux comes entirely from gas ionized by young stars, we can estimate the star formation rate via $\dot{M}(M_\odot\ \mathrm{yr}^{-1}) = 3.9 \times 10^{-8}$ $L_{\mathrm{H}\alpha}(L_\odot)$ (e.g., Gallagher, Hunter, and Tutukov 1984), assuming a Salpeter function between stellar masses of 0.1–100 $M_\odot$. Derivation of this equation assumed star formation continuing for a long time compared with the lifetime of the stars that dominate the excitation of the gas. It is fashionable to consider "truncated" or "bimodal" mass functions, but this adds additional complications with, in our view, little justification at present. Without further information, we assume that star formation is proceeding in this system with approximately the same characteristics as found in the Milky Way and that the observed Hα emission arises solely as a result of star birth. With these assumptions, we find the derived star formation rate in the galaxy to be about 18 $M_\odot$ yr^{-1}, using the line flux of Heckman, Armus, and Miley (1987) uncorrected for extinction. In § III*b* we estimated $A_V = 2$ mag averaged over the galaxy, or $A_{H\alpha} = 1.4$ mag. In this case we adopt a screen model for the dust distribution, since this may be a fair approximation for line emission from dusty star-forming regions but cannot be physically correct for the emission from the stellar continuum. Correction for extinction then gives a star formation rate of about 65 $M_\odot$ yr^{-1}, a value which is only a few times that derived for two nearly normal giant spirals. Thus, how many young stars would have formed anyway, despite the merger? A high star formation rate should translate into a high supernova rate, which would then be a test for models of massive stellar creation in this object. From Thronson and Greenhouse (1988), we can estimate the supernova rate via R_{SN} yr$^{-1} \approx 0.004\dot{M}_*$ $M_\odot$ yr^{-1}, or $\sim$0.25 yr^{-1}. This rate is lower than the upper limit that we derive from our infrared imaging. Over the course of this program, NGC 6240 was observed at about 6 month intervals for 18 months without detecting any pointlike brightening. A Type II supernova should be brighter than $m \sim 18$ in all near-infrared bands for at least several months. That is, the observed supernova rate is less than $\sim$1 yr^{-1} in the 30″ core.

Before we go on to the question of continuing star formation versus "bursts," we point out that the Hα luminosity is appropriate to the luminosity of the young stellar component that we estimated in § III*b*. The stellar photospheric flux is about 60 times the Hα flux for a distribution of stars that follows the Salpeter function from 0.1 to 100 $M_\odot$, as derived from studies of actively star-forming galaxies (Gallagher, Hunter, and Tutukov 1984; Thronson and Telesco 1986). For the line flux estimated for NGC 6240, then, $L_{*,\rm young} \approx 1 \times 10^{11}$ $L_\odot$, close to the value that we derived for the stars that dominate the *U*- and *B*-band emission. The extinction within the object is a major uncertainty in this estimate. An additional important source of luminosity may be the active nucleus (DePoy, Becklin, and Wynn-Williams 1986).

We now consider the question of efficiency of star formation, which is defined as the mass of new stars divided by the mass of material from which they formed, which is probably molecular, $M_{*,\rm young}/M(H_2)$. This is one of the most seductive global parameters currently derived for galaxies, in a large part because it is of major importance in our understanding of galaxian evolution but also because both numerator and denominator in the ratio are liable to major systematic uncertainties. We assure the reader who has waded through this paper to this point that we have no intention of discussing these uncertainties here. We shall refer to detailed discussions elsewhere.

The molecular mass of NGC 6240 has been estimated in a pair of ways, from millimeter-wave rotational transitions of CO (Sanders and Mirabel 1985; Sanders *et al.* 1986) and from the thermal emission from cool dust presumably associated with the molecular gas (Draine 1990). From the CO observations, $M(H_2) \approx 2 \times 10^{10}$ $M_\odot$, using a conversion factor between CO line strength and molecular mass appropriate to the Milky Way. This is questionable (e.g., Maloney 1990). From the observed infrared continuum, Draine estimated $M_{\rm gas} = (0.66\text{–}8.9) \times 10^{10}$ $M_\odot$, depending almost entirely upon the amount of cool ($T_d \sim 15$–25 K) dust that is present. Another limitation of using the thermal dust emission is that it is rarely clear what component of the gas is associated with the dust emission. Thus, this estimate of the H_2 mass is an upper limit, given that some dust in emission at far-infrared/submillimeter wavelengths is mixed with the atomic gas. Until further information is available to us, we adopt a molecular mass of 2×10^{10} $M_\odot$, equal to the value derived from the CO observations and about midway in the range derived from analysis of the dust emission. We consider that this estimate is uncertain by at least a factor of 2.

Although our preference is for a measure of the star formation rate that is less sensitive to the uncertainties of obscuration, we now use the corrected Hα flux to derive a mass of young stars, once again assuming a Salpeter function from 0.1 to 100 $M_\odot$. Thronson *et al.* (1989) recently calculated that the mass of stars associated with the visual line luminosity is $M_{*,\rm young}(M_\odot) = 0.078L_{H\alpha}(L_\odot)$. For NGC 6240, we estimate that $M_{*,\rm young} \approx 1.3 \times 10^8$ $M_\odot$, which gives $M_{*,\rm young}/M(H_2) \sim 0.65\%$. For comparison, Thronson *et al.* compiled ratios from the literature derived similarly for isolated spiral galaxies and found a global average of 0.1%, with a variation of about a factor of 3. This result strongly suggests that the efficiency of star formation in NGC 6240 is higher than in isolated galaxies, presumably as a result of the collision. Unfortunately, uncertainties in these calculations are considerable: if the upper range of the interstellar mass derived by Draine (1990) is correct and if this mass is molecular, then the efficiency that we would derive is only 0.14%, equal to that derived for normal galaxies. Stated in another way, the stars observed to be forming may have done so anyway without the effects of the violent merger, and more work needs to be done before an unambiguous association can be made between star birth and collisions.

This conclusion is supported by considering another, but far less satisfactory global ratio, $L_{\rm IR}/M(H_2)$, which is sometimes hauled out as a measure of efficiency. If the light from new stars overwhelms the dust heating by other sources, then the infrared flux can be used as a measure of the number of young stars (e.g., Rowan-Robinson and Crawford 1989). This is not the case for NGC 6240—and plausibly for other merging systems—and the high ratio for this object, $L_{\rm IR}/M(H_2) = 24$, is insufficient support for the interpretation of efficient star formation (e.g., Sanders *et al.* 1986).

Finally, we estimate the lifetime of the ISM in NGC 6240 against the vigorous star formation observed to be taking place. If the rate of star formation follows an exponential, $\dot{M}_* \propto \exp(-t/\tau_R)$, with some time scale, the "Roberts time" τ_R, then $\tau_R = M(H_2)/\dot{M}_* \approx (0.1\text{–}1.4) \times 10^9$ yr, using the range of masses of the ISM derived for this object by Draine (1990). The lower value for this ratio suggests that a "burst" of some kind is taking place, but the upper value is only about a factor of 2 below values derived for normal, isolated galaxies. Unfortunately, the uncertainties in our calculations are again so large that a firm conclusion about the lifetime of gas in this object is as elusive as any conclusion about the efficiency of star formation. We are content to state that the lifetime for the ISM is probably at least few times 10^8 yr and may be much longer than is usually implied by the term "burst."

d) A Note about Arp 220

It is likely that assignment of the title "prototype" to an object is more misleading than it is revealing. As an antidote to this notion, now that we have proposed an alternative explanation for much of the heating of the dust in NGC 6240, we succumb to temptation and write a few words about the other highly popular "ultraluminous" galaxy, Arp 220.[7] We intend the following to be highly abbreviated. Good discussions of Arp 220, usually following conventional "starburst" interpretations, may be found in Joy *et al.* (1986), Heckman, Armus, and Miley (1987), DePoy, Becklin, and Geballe (1987), Smith *et al.* (1988), Doyon, Joseph, and Wright (1989), Smith, Aitken, and Roche (1989), Solomon, Radford, and Downes (1990), and Graham *et al.* (1990). There is substantial disagreement in the literature about the energetics of this source. As with NGC 6240, a very large far-infrared luminosity and large infrared-to-visual ratio have attracted a great deal of comment. At an adopted distance of 72 Mpc, $L_{\rm IR} = 8 \times 10^{11}\ L_{\odot}$ (40–120 μm).

We first derive the estimated luminosity associated with star formation using the method described in § III*b*. Heckman, Armus, and Miley (1987) observe an Hα luminosity over an area about 25″ across of $L_{\rm H\alpha} = 1.1 \times 10^{41}$ ergs s^{-1} uncorrected for extinction. Smith *et al.* (1988) concluded that the extinction within the object at H is about 0.5–1 mag, assuming a screen of dust, or $A_{\rm H\alpha} \approx 2.1$–4.1 mag with the extinction curves in Draine (1989). Later work (Doyon, Joseph, and Wright 1989; Graham *et al.* 1990) estimated an obscuration near the high end of this range. If, as for nearly normal, actively star-forming galaxies, the total luminosity emitted by young stars is 60 times that of the Hα luminosity, then the radiation available to heat the grains from star formation is 1.1–7.6 $\times 10^{10}\ L_{\odot}$, where the range is due to the variation in the poorly known extinction. This fails by an order of magnitude or more to power the far-infrared emission. The weak hydrogen recombination lines in this "starburst" object have been commented on by others (e.g., Beck, Ho, and Turner 1989), and over most of the object there is no evidence for the deep 2.3 μm CO absorption expected for a large population of young, red supergiants (Doyon, Joseph, and Wright 1989). Star formation is active in Arp 220, but available evidence is that it makes a puny contribution to the total energetics.

Similarly, the efficiency of star formation in Arp 220 may be about normal for gas-rich objects, and, as with NGC 6240, we argue that stellar birth might be taking place in this object anyway, without recourse to the collision. For a Salpeter distribution of stellar masses from 0.1 to 100 $M_{\odot}$, the mass of young stars can be estimated from $M_{*,\rm young}(M_{\odot}) = 0.078 L_{\rm H\alpha}(L_{\odot})$ (Thronson *et al.* 1989). From the corrected Hα flux, $M_{*,\rm young} = (1.4\text{–}10) \times 10^7\ M_{\odot}$. As with interstellar mass determinations for other "ultraluminous" galaxies (e.g., Maloney 1990), gas mass determinations for Arp 220 are uncertain. Observations of the rotational emission lines of CO have been used to derive $M(\rm H_2) = 1.4 \times 10^{10}\ M_{\odot}$ (Sanders and Mirabel 1985; Scoville *et al.* 1986), while astronomers using the long-wavelength continuum emission from cool dust have estimated gas masses over a very wide range, $M_{\rm gas} = (0.9\text{–}10) \times 10^{10}\ M_{\odot}$, due in large part to the uncertainty in estimating the dust temperature (Thronson *et al.* 1987; Eales, Wynn-Williams, and Duncan 1989). If we take the range derived from the cool dust emission as giving the upper and lower bounds to the true interstellar molecular gas mass, then the corrected Hα emission gives a star formation efficiency falling in the range 0.014%–1%. These limits are so broad that they have little use, except to show that the efficiency is much higher than that found for isolated normal galaxies only when *both* the largest corrected visual line flux plus the smallest estimate for the $\rm H_2$ mass are used.

In contrast to NGC 6240, the light from the older stellar population fails by a large factor to power most of the far-infrared emission, if our coarse approximation to the dust extinction is satisfactory. Using the stellar flux at J (Smith *et al.* 1988) as the best available measure of the light from older stars, but using multiaperture V and K photometry for the large correction for an incomplete measure of the total source flux (Joy *et al.* 1986; Smith *et al.* 1988), we estimate $m_J = 11.1$, or, at a distance of 72 Mpc, $M_J = -24.0 \rightarrow -24.8$, corrected for extinction. Using our results from Table 3, $M_{\rm bol} = -22.6 \rightarrow -23.4$, giving $L_{*} \approx (0.9\text{–}2) \times 10^{11}\ L_{\odot}$ over about a 2′ area. Like the luminosity available from the very young stars, the older stars fail by a large factor to power the far-infrared emission.

With radiation from both young and old stars failing by significant factors to explain the total infrared luminosity from Arp 220, by default our observations support the interpretation of this object as something like a quasar in the making (Sanders *et al.* 1988; Graham *et al.* 1990).

IV. A SIMPLE GENERALIZATION TO OTHER GALAXIES

A major argument of our paper is that, in addition to the more rococo explanations for the high infrared luminosities of merging galaxies—lurid starbursts, Seyfert and active nuclei, cloud-cloud collisions—two prosaic sources of dust heating, the light from the older stellar population and continuing star formation, may make important contributions. Now we shall generalize our arguments to other luminous, apparently merging, systems. Our information on these other objects is taken primarily from surveys in the literature and is therefore much more limited than that which we have for NGC 6240. We also wish to reinforce the arguments that older stars can play a major role in heating the dust in normal galaxies (e.g., Persson and Helou 1987; Cox and Mezger 1989; Rowan-Robinson and Crawford 1989; Bothun, Lonsdale, and Rice 1989; Rowan-Robinson 1990). One point that we will emphasize in this section is that much past work has systematically underestimated the stellar luminosity in galaxies and, consequently, the importance of this source of dust heating. In the following discussion, we adopt the questionable conventional assumption that the extinction in galaxies is limited to a mythological overlying screen. For small values of extinction, this fiction is not a serious problem, but Bruzual, Magris, and Calvet (1988) and Disney, Davies, and Phillipps (1989) have vigorously called into question the widespread notion of small visual extinctions in nearly normal galaxies.

We base our discussion first on Figure 9, a histogram of the ratio of total stellar luminosity to the far-infrared (about 40–120 μm) luminosity, $L_{*}/L_{\rm IR}$. The lower panel shows the distribution for isolated nearly normal, almost exclusively spiral galaxies, taken from Soifer *et al.* (1989). The bolometric stellar luminosity, L_{*}, was derived from our Table 3, which can be rewritten for blue magnitudes corrected for absorption as

[7] Some readers may wonder why we do not discuss M82, THE PROTOTYPICAL STARBURST GALAXY. Our answer is that life is too short: M82 is overrated, overstudied, and was *not* overhead while the ARC camera was on the WIRO telescope. Our good fortune. Our short polemic on the misapplication of the results from M82 appears in Thronson *et al.* (1990).

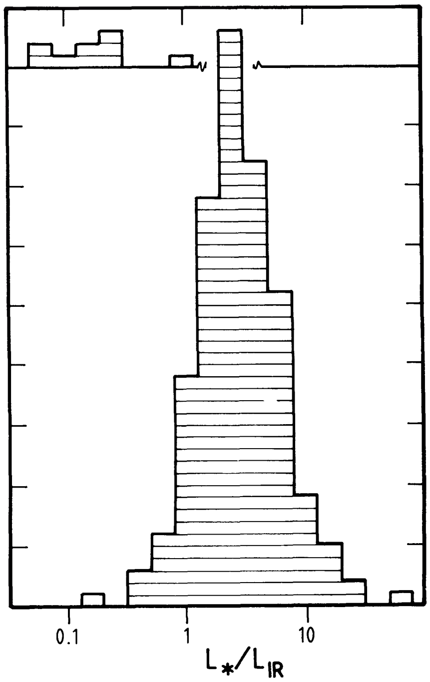

FIG. 9.—Histograms of the ratio of estimated total stellar luminosity to the observed far-infrared luminosity, L_*/L_{IR} for normal, predominantly isolated spirals (*lower histogram*) and "ultraluminous" galaxies (*upper histogram*). Radiation from the older stellar population is sufficient to power the infrared sources in the normal galaxies and may make an important contribution to the dust heating in the sample of very luminous objects.

$L_*(L_\odot) = 2.4 \times 10^{12} D^2(\mathrm{Mpc}) 10^{-0.4 m_{B,0}}$. For this equation, we use the magnitudes corrected for internal and external absorption, $B_T^{0,i}$, from Sandage and Tammann (1981). Only about a third of the galaxies for which Soifer *et al.* (1989) tabulate *IRAS* flux densities have blue magnitudes in Sandage and Tammann, but this sample is sufficient for our demonstration.

Far-infrared luminosities that we use were derived from 60 and 100 μm *IRAS* flux densities via $L_{IR}(L_\odot) = 6 \times 10^5 D^2(\mathrm{Mpc})[2.58 F_{60}(\mathrm{Jy}) + F_{100}(\mathrm{Jy})]$ (Lonsdale *et al.* 1985). The ratio of the two luminosities may be written as

$$\frac{L_*}{L_{IR}} = 4.0 \times 10^6 \, \frac{10^{-0.4 m_{B,0}}}{2.58 F_{60} + F_{100}} \, . \tag{1}$$

Red or near-infrared photometry gives an estimate of the luminosity of the older stellar population that is less susceptible to uncertainties in a galaxy's history and obscuration than is the blue flux. However, such data are not yet available for most systems that have been observed with *IRAS*. However, the average values derived for converting photometry to bolometric magnitudes (Table 3) apply to spiral galaxies, the majority of sources in the compilation of Soifer *et al.* (1989). Thus, adopting the blue magnitude should be satisfactory for this preliminary study. The blue extinction that we take from Sandage and Tammann (1981) is not measured for each galaxy but is derived from models of the obscuration within the Milky Way and internal to "average" disk galaxies (but see Bruzual, Magris, and Calvet 1988; Disney, Davies, and Phillipps 1989). While not accurate for individual objects, this absorption should produce satisfactory average results for a large sample of objects. The average total blue extinction from Sandage and Tammann (1981) for the galaxies plotted in the histogram is about 0.6 mag.

The upper part of Figure 9 shows a histogram of stellar-to-infrared luminosities derived for the extremely luminous galaxies compiled by Sanders *et al.* (1988). These authors obtained visual and near-infrared photometry for 10 extragalactic systems with $L_{IR} \approx 10^{12}$ $L_\odot$, very luminous objects by any standard. Because of the advantages of very red photometry already discussed, we use the i (0.82 μm) magnitudes of Sanders *et al.*, taken with the largest aperture that they report, 50″. Again using the results from our Table 3, we can estimate total luminosity of the older stellar population via $L_*(L_\odot) = 3.8 \times 10^{11} D^2(\mathrm{Mpc}) \times 10^{-0.4 m_{i,0}}$, which then gives

$$\frac{L_*}{L_{IR}} = 6.3 \times 10^5 \, \frac{10^{-0.4 m_{i,0}}}{2.58 F_{60} + F_{100}} \, . \tag{2}$$

For the very luminous systems, we have the advantage of using a measured value of the extinction of the stellar light derived by Sanders *et al.* (1988) from Balmer line ratios. To derive unextinguished magnitudes, we adopt $A_i = 1.5E(B-V)$ (Draine 1989). Obviously, it is likely that the stellar light is not extinguished by the same amount as derived for the visual emission lines, but this is the best estimate of the obscuration available to us. We point out that for the 10 systems observed by Sanders *et al.* values for A_V are in the range 3–6, under the assumption of an overlying screen. These values are roughly supported by a near-infrared two-color diagram (Fig. 14 of Sanders *et al.*), which can be interpreted as normal $J-H$ galaxy colors for the merging systems, extinguished by approximately the same amount as the visual emission lines. This amount of obscuration is as much as an order of magnitude greater than that usually proposed for isolated galaxies (Sandage and Tammann 1981; Moorwood, Véron-Cetty, and Glass 1986), emphasizing that these merging galaxies are systems in which nearly all the stellar light has been absorbed by the interstellar dust. Effective dust absorption also means that the extremely large infrared-to-visual light ratios, so often commented upon in the literature, are at least as much an effect of a highly obscured visual source as they are a result of enormously high infrared luminosities.

Further insight is possible by considering Figure 10, a plot of the infrared-to-visual luminosity ratio versus the stellar luminosity, derived as described above, where the points from Soifer *et al.* (1989) are shown as the small filled circles. In this diagram, we also have included data on some popular galaxies taken from Rice *et al.* (1988), also shown as small filled circles. Diagrams of L_{IR}/L_* versus L_{IR}, or near-equivalents, have been discussed widely in the literature, but we consider the source of the infrared luminosity to be so varied and ambiguous as to make this alternative plot unrevealing. Data on the "ultraluminous" galaxies from Sanders *et al.* (1988) are shown as large open circles. Our figure also includes values derived from the study of dwarf and irregular galaxies by Hunter *et al.* (1989), shown as large filled circles, and S0 and S0/a galaxies (Thronson *et al.* 1989), shown as crosses. For the irregulars, the extinction-corrected blue magnitudes in Hunter *et al.* were used to derive L_*. Distances for all the objects were derived either by adopting values from the original work or by assuming a Hubble constant of 75 km s^{-1} Mpc^{-1}. The inevitable distance uncertainties in extragalactic astronomy have no consequence in the following discussion.

In many respects, our Figure 10 is qualitatively very similar to Figure 5*b* of Soifer *et al.* (1987), although we disagree with these authors on its interpretation (see also Sanders *et al.* 1988;

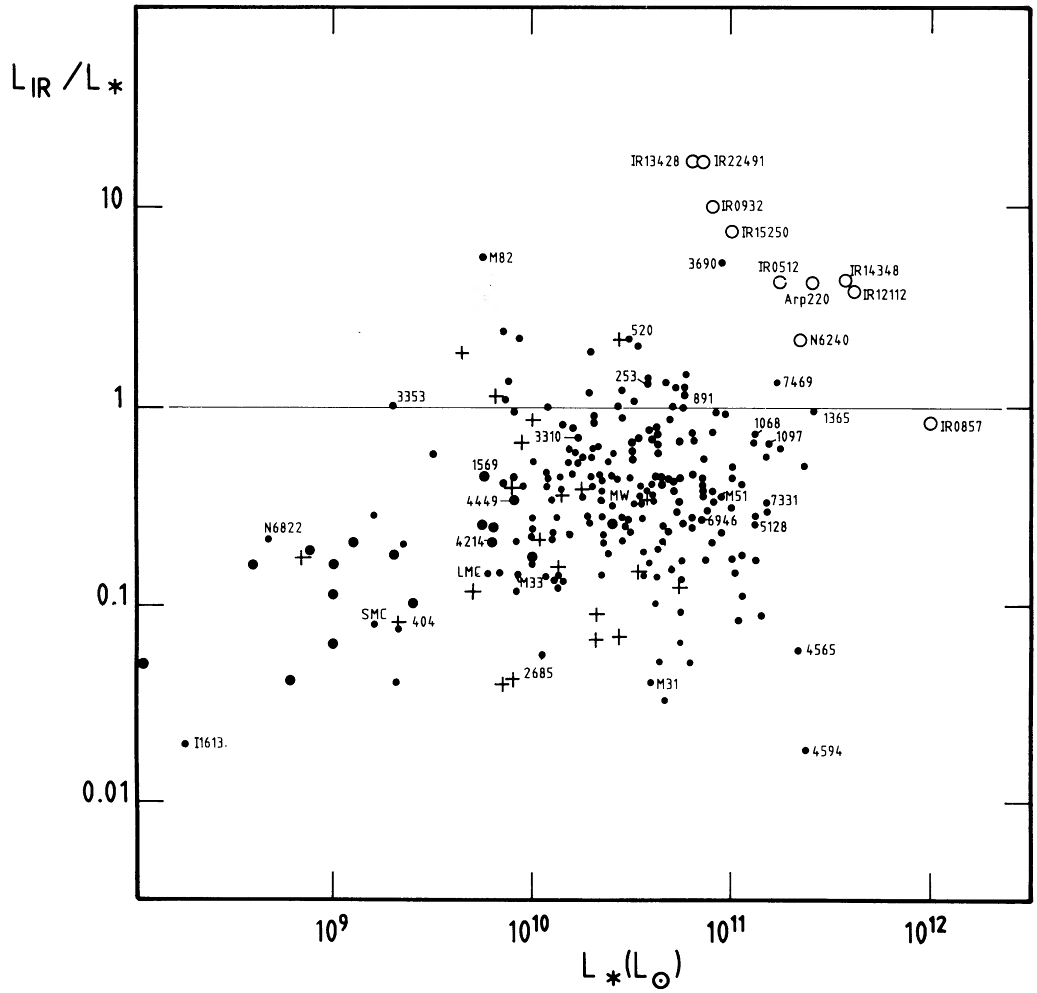

FIG. 10.—Infrared-to-visual luminosity ratio vs. estimated stellar luminosity for normal, predominantly isolated spirals (*small filled circles*; from Rice *et al.* 1988 and Soifer *et al.* 1989), dwarfs and irregulars (*large filled circles*; from Hunter *et al.* 1989), S0 and S0/a galaxies (*crosses*; from Thronson *et al.* 1989), and the "ultraluminous" galaxies of Sanders *et al.* (1988) (*large open circles*). Derivation of the plotted quantities is discussed in § IV, where we emphasize that visual extinctions were *estimated* for galaxies represented by the small filled circles. That is, although some specific objects are identified, their locations are approximate, and more accurate estimates of internal extinctions are required (Appendix). Messier, IC, and NGC numbers are given for some well-known and beloved objects. "MW" represents the Milky Way. A horizontal line is drawn at the locus below which an older stellar population is potentially capable of solely powering the observed infrared luminosity. We argue that the scatter in points below this line is largely a consequence of significant variations in the internal extinction in normal galaxies, along with the differences in the birthrate of new stars and an occasional active nucleus of some kind.

Soifer *et al.* 1989). In part, our alternative interpretation is a consequence of our attempt to estimate the available stellar luminosity in these objects, as emphasized by the horizontal line in our figure at the locus below which old stars have the potential to solely power the observed far-infrared emission from the dust (i.e., $L_{IR} \leq L_*$), given sufficient interstellar absorption. A majority of normal, isolated spiral, irregular, lenticular, and dwarf galaxies lie below the line. Scatter in the figure is a consequence of the large range of internal absorption suffered by typical photons: most of the variation in L_{IR}/L_* in Figures 9 and 10 can be mimicked by $A_V \sim 0.1$–1 mag, entirely reasonable values. Active star formation and the occasional active or Seyfert nucleus will also be important heating sources, and will introduce scatter to the figure. Similar conclusions were reached in the detailed analysis of *IRAS* data by Rowan-Robinson and Crawford (1989; see their Fig. 6).

Both our figures contradict the identification of many *IRAS*–selected galaxies as especially "infrared-active" (Soifer *et al.* 1987), since we find $L_{IR}/L_* \leq 1$ in the overwhelming majority of objects chosen for their infrared brightness from the *IRAS* data (Fig. 10, *filled circles*). Earlier work on the infrared-to-visual ratio, or its near-equivalents, often indicated that $L_{IR}/L_* \gg 1$ and did not show as distinct a boundary at $L_{IR}/L_* \approx 1$ as do our figure and histogram (e.g., Moorwood, Véron-Cetty, and Glass 1986; Soifer *et al.* 1987, 1989). One explanation is that many past estimates of the stellar flux underestimated the available energy of the older stars, even before consideration of the effects of extinction. For example, deriving the stellar luminosity via $L \propto \nu F_\nu$ for the *B* band produces a numerical value a factor of 2.5 lower than that which we derive using the values compiled in Table 3. Moreover, our work attempted a correction to the visual extinction, which averaged about $A_B = 0.6$ mag for the normal galaxies and is a major effect for merging systems. In other words, much past work on the visual flux from older stars in normal galaxies produced values for the stellar luminosity that were systematically almost a factor of 5 lower than our estimates.

Finally, we disagree with the earlier interpretations that the lack of correlation between L_{IR}/L_* and L_* means that L_{IR} and L_* are decoupled (Soifer *et al.* 1989). In our view, they can be *highly* coupled, intimately connected by the effects of absorption in the ISM. The small numbers of dwarf and irregular galaxies in our figure (Hunter *et al.* 1989), which were not included by earlier authors, support this interpretation, since these less luminous galaxies are also more open systems and less dusty. Their internal dust is less effective at intercepting the general interstellar radiation field, so, on average, L_{IR}/L_* decreases as L_* becomes smaller, as our figure indicates.

"Ultraluminous" galaxies (Sanders *et al.* 1988) are found at the upper right in Figure 10, not extremely different in location from the luminous giant spirals, consistent with the arguments expressed throughout this paper. Had we not corrected the observed visual flux for an estimated extinction, L_{IR}/L_* for the merging systems would have been very different from the positions for nearly normal spirals and would support what we consider to be more extreme interpretations of the infrared emission from merging galaxies. Our figure supports a conservative interpretation for both the infrared emission and the very high L_{IR}/L_* ratio observed for many merging galaxies. The two best-known examples of this type of object, NGC 6240 and Arp 220, lie only modestly above the $L_{IR} = L_*$ line, which indicates that an important fraction of the infrared luminosity may be supplied by the older stellar population. The remainder of the emission is presumably supplied by star formation and/or an active nucleus.

The nuisance, M82, is isolated in our figure, consistent with our opinion that this object may be intriguing but is also misleading when considered as a model for objects such as NGC 6240 or active global star formation in normal galaxies (see also Verter and Rickard 1989; Thronson *et al.* 1990).

V. SUMMARY

We have presented and interpreted U, R, J, H, and K images of the popular merging galaxy pair NGC 6240. While we agree with the description of this system as a pair of giant, gas-rich galaxies in collision, we argue that an "ultraluminous" "super-starburst" is neither the most obvious nor the sole explanation for many of the observations of this system. In particular, absorption of the light from an older stellar population by a disrupted dusty ISM can contribute a large fraction of the observed emission at long wavelengths. We estimate this source of dust heating to make up between one-fifth and one-half of the total infrared luminosity in this galaxy, depending upon the details of the interstellar absorption. New blue stars, in contrast, contribute roughly a fourth of the heating. In addition, this stellar creation may be little more then the continuation of star birth that would be going on anyway in a gas-rich environment, as distinct from a short-lived "burst" that is directly related to the merger. However, based on data from the literature, the efficiency of star birth is higher than that derived for isolated, gas-rich galaxies, within the considerable uncertainties. Of course we disagree with many past interpretations of the ratio $L_{IR}/M(H_2)$ in this object and, perhaps, other merging systems.

It is unlikely that NGC 6240 is unique, and more prosaic sources of dust heating should be considered for other merging systems. As an example, we consider the other popular "ultraluminous" infrared galaxy, Arp 220, for which we also estimate that the flux from young stars is insufficient to explain the high far-infrared luminosity. As with NGC 6240, the older stellar population probably contributes more toward heating the interstellar dust. However, in this object, both types of stellar light fail by a large factor to match the observed infrared luminosity, and another source of dust heating is necessary, perhaps energy supplied by a dust-enshrouded energetic nucleus.

As part of our analysis of NGC 6240, we adapt model galaxies to derive a series of conversions from monochromatic magnitudes to stellar bolometric luminosities. This allows us to estimate the energy available from old stars to heat the interstellar dust. The stellar luminosity is most closely correlated with the I emission, although uncertain dust extinction may make longer wavelength (H or J) photometry more useful. The older stellar population in nearly normal galaxies is substantially more luminous than seems to have been realized, judging from the literature, which reduces some of the sharp distinctions that have been drawn between nearly normal giant galaxies and "ultraluminous" systems.

We expand our discussion to consider the infrared-to-stellar light ratio in a representative sample of dwarf, spiral, lenticular, "*IRAS*," and "ultraluminous" galaxies taken from the literature. We disagree with almost every published interpretation of this type of ratio of which we are aware. First, the infrared emission can be, for many isolated galaxies, closely coupled to the light of the older stellar population through the dusty interstellar medium, even for infrared-selected systems, although star formation and/or an active nucleus will make important contributions toward heating the dust. We tentatively find that the older stellar population contributes an important fraction to the total infrared luminosity of other "ultraluminous" starburst galaxies. We also emphasize the importance of the dusty, disrupted ISM in playing the major role in producing the large ratios of $L_{IR}/L_{optical}$ that have been used as hallmarks of something bizarre in merger systems.

In our appendix we describe a simple, more physically reasonable alternative to the overlying screen model for dust extinction in galaxies. Throughout this paper we have emphasized the serious limitations of most adopted models (including our own) of the effects of dust extinction.

We criticize the use of M82 as a prototype of anything useful.

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APPENDIX

REFLECTIONS ON THE EFFECTS OF THE RELATIVE DISTRIBUTION OF DUST AND STARS IN GALAXIES

With few exceptions, the majority of astronomers, including ourselves, treat the relative distribution of gas and dust in galaxies with the same consideration that we might give to, say, San Francisco street mimes or former US presidential candidates. The vast majority of the time we are happily ignorant of their existence, but, when confronted by one of these minor plagues of American life, we halt, evade, sidestep, and become a bit confounded, all the while wishing for a handy baseball bat. However, just as urbanization means more frequent contact with difficult situations, so too do recent results in the astronomical literature require a more careful evaluation of the effects of dust in galaxies.

The standard correction for the effects of dust in galaxies is to assume that continuum or line emission is obscured by a single overlying screen so that the observed intensity decreases as $I_\lambda \propto \exp(-\tau_\lambda)$. Such simple models are wrong, but may be adequate: for average values of A_V less than a few tenths of a magnitude, the effects of uncertainties in the dust distribution are small. However, in the case of a disrupted, dusty ISM, such as in NGC 6240 and other vigorously merging galaxies (e.g., Sanders *et al.* 1988), the total extinction is in excess of about 0.5 visual magnitudes, and the effects of adopting different dust distributions are significant. Worse yet, Bruzual, Magris, and Calvet (1988) and Disney, Davies, and Phillipps (1989) argue that the obscuration in isolated *normal* galaxies has been systematically underestimated in past work.

Our contribution to improved understanding of the effects of dust in normal galaxies appears more fully in Thronson, Rubin, and Ksir (1990) and Barnaby and Thronson (1990). In this appendix, we wish to consider one simple alternative analytical model for extinction in the particular case of badly disrupted dusty galaxies, such as mergers. Because three of the four authors of this paper are conservative by nature, we chose to put this analysis into an appendix, rather than include yet another contrary discussion in the main body. Readers are encouraged to read Keel (1990) for a good description of the observational data on extinction in NGC 6240.

Our basic assumption is simple. Instead of a fictional overlying screen of dust within disrupted galaxies, we instead argue that the dust and stars within such objects become so jumbled that a better approximation—but only an approximation—is a uniform mixture of dust and stars. If we assume that the scattering optical depth is less than roughly unity, so that light at visual and near-infrared wavelengths is only removed from our view, with little scattered into it, the observed intensity depends on the total line-of-sight absorption optical depth as

$$I_\lambda = I_{\lambda,0} \frac{1 - \exp(-\tau_\lambda)}{\tau_\lambda} . \tag{A1}$$

Comparison is presented in Table 4 of observed intensities for both the overlying screen and the uniform dust/stars mixture. There we assume, as we did in the body of our paper, that both models have $A_V = 2$ mag ($\tau_V = 1.8$), although this particular value was taken from the literature under the assumption of an overlying screen. The extinction in NGC 6240 averaged over the entire source is uncertain, and we adopt a single value for A_V primarily to show the difference in observed colors for the same amount of dusty ISM distributed in different ways in an object. Given that a model of uniformly mixed dust and stars produces a smaller effect on the emitted light, it is possible that the true A_V in this object is much greater than 2 mag. However, adopting larger total extinctions also means including the effects of scattering, a much more complicated radiative transfer problem (Bruzual, Magris, and Calvet 1988).

The effects of extinction on intensity are reduced if the dust is more widely distributed throughout the stellar system than in the overlying screen (Table 4; Bruzual, Magris, and Calvet 1988; Disney, Davies, and Phillipps 1989). Vice versa, the amount of dust within a seriously disrupted system is significantly underestimated if it is incorrectly assumed to overlie the stars and is investigated via visual extinction. Although our model and Table 4 are meant to present only very rough alternatives to standard assumptions, the resultant values are indicative of the problems of correcting both observed fluxes and colors for obscuration. Deriving true colors is, as always, more serious at shorter wavelengths, where the effects of the dust are more serious. Assuming an overlying screen, for example, leads to calculating bluer intrinsic stellar colors and incorrectly concluding, perhaps, that an object has undergone a period of enhanced stellar formation—a "starburst." The very red and near-infrared colors are less affected by uncertain dust distributions, which is why we produced a method to estimate the total stellar luminosity via red and infrared photometry (§ III*b* and Table 3).

We present the reader with a choice here: adoption of an overlying screen is incorrect, while choosing a uniform dust/stars mixture is merely inadequate. For extinctions greater than a few tenths of a magnitude, the screen model leads to very significant errors in derived intrinsic colors and intensities. We expect that our own alternative model begins to break down for A_λ in excess of about 2 mag, where scattering becomes a significant effect. That is, in this discussion we probably extended our approximate model to the limit of its applicability. Then, there is the implicit assumption that the observed stellar continuum emission and gaseous line emission can be corrected using the same model. This is probably incorrect, even as a rough approximation. Hydrogen recombi-

TABLE 4

INTENSITIES FOR A PAIR OF SIMPLE DUST DISTRIBUTIONS

I/I_0	U	B	V	R	I	J	H	K
Screen.........	0.06	0.10	0.16	0.27	0.42	0.60	0.73	0.85
Mixed.........	0.32	0.39	0.45	0.56	0.66	0.78	0.86	0.91

NOTE.—Ratio of observed to intrinsic intensity for an assumed overlying screen and a uniform mixture of stars and dust, with $A_V = 2$ mag in both cases.

nation line emission from H II regions, for example, may be more likely extinguished by the dust within the remnant cloud from which the hot young stars recently formed, rather than by the extended, disrupted ISM that obscures the majority of the stellar light. Consequently, the overlying screen model would be a better approximation than our uniform mixture alternative. Similarly, the extinction to different stellar populations might not be approximated by the same dust distribution model. As with the H II regions, young, blue stars may be preferentially obscured by local material, while the older, redder stars would be expected to suffer the effects of the more widely distributed grains.

REFERENCES

Arimoto, N., and Yoshii, Y. 1986, *Astr. Ap.*, **164**, 260.
Armus, L., Heckman, T., and Miley, G. 1987, *A.J.*, **94**, 831.
Barnaby, D., and Thronson, H. A. 1990, *Ap. J.* (*Letters*), submitted.
Beck, S. C., Ho, P. T. P., and Turner, J. 1989, in *Proc. 22d ESLAB Symposium, Infrared Spectroscopy in Astronomy*, ed. B. H. Kaldeich (Paris: ESA), p. 247.
Bothun, G., Lonsdale, C., and Rice, W. 1989, *Ap. J.*, **341**, 129.
Boulanger, F., and Pérault, M. 1988, *Ap. J.*, **330**, 964.
Bruzual, G., Magris, G., and Calvet, N. 1988, *Ap. J.*, **333**, 673.
Cox, P., and Mezger, P. 1989, *Astr. Ap. Rev.*, **1**, 49.
DePoy, D. L., Becklin, E. E., and Geballe, T. R. 1987, *Ap. J.* (*Letters*), **316**, L63.
DePoy, D. L., Becklin, E. E., and Wynn-Williams, C. G. 1986, *Ap. J.*, **307**, 116.
Descartes, L., Majewski, S., Thronson, H. A., and Hereld, M. 1988, *Bull. AAS*, **20**, 999.
Disney, M., Davies, J., and Phillipps, S. 1989, *M.N.R.A.S.*, **239**, 939.
Doyon, R., Joseph, R. D., and Wright, G. S. 1989, in *Proc. 22d ESLAB Symposium, Infrared Spectroscopy in Astronomy*, ed. B. H. Kaldeich (Paris: ESA), p. 477.
Draine, B. T. 1989, in *Proc. 22d ESLAB Symposium, Infrared Spectroscopy in Astronomy*, ed. B. H. Kaldeich (Paris: ESA), p. 93.
———. 1990, in *The Interstellar Medium in Galaxies*, ed. H. A. Thronson and J. M. Shull (Dordrecht: Kluwer), p. 483.
Eales, S. A., Wynn-Williams, C. G., and Duncan, W. D. 1989, *Ap. J.*, **339**, 859.
Fischer, J., Geballe, T. R., Smith, H. A., Simon, M., and Storey, J. W. V. 1987, *Ap. J.*, **320**, 667.
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.
Fried, J. W., and Ulrich, H. 1985, *Astr. Ap.*, **152**, L14.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Gallagher, J. S., Hunter, D. A., and Tutukov, V. 1984, *Ap. J.*, **284**, 544.
Graham, J. R., Carico, D. P., Matthews, K., Neugebauer, G., Soifer, B. T., and Wilson, T. D. 1990, *Ap. J.* (*Letters*), **354**, L5.
Guhathakurta, P., Tyson, J. A., and Majewski, S. 1990, *Ap. J.* (*Letters*), **357**, 9.
Gullixson, C. A., Boeshaar, P. C., Tyson, J. A., and Seitzer, P. 1990, *A.J.*, submitted.
Harwit, M., and Fuller, C. E. 1988, *Ap. J.*, **328**, 111.
Harwit, M., and Pacini, F. 1975, *Ap. J.* (*Letters*), **200**, L127.
Heckman, T. M., Armus, L., McCarthy, P., van Breugel, W., and Miley, G. K. 1987, in *Star Formation in Galaxies*, ed. C. J. L. Persson (Pasadena: JPL), p. 461.
Heckman, T. M., Armus, L., and Miley, G. K. 1987, *A.J.*, **93**, 276.
Hereld, M., Harper, D. A., and Pernic, R. 1990, in preparation.
Hunter, D. A., Gallagher, J. S., Rice, W., and Gillett, F. 1989, *Ap. J.*, **336**, 152.
Joseph, R. D., and Wright, G. S. 1985, *M.N.R.A.S.*, **214**, 87.
Joy, M., Lester, D. F., Harvey, P. M., and Frueh, M. 1986, *Ap. J.*, **307**, 110.
Keel, W. C. 1989, *Sky and Tel.*, **77**, 18.
———. 1990, *A.J.*, submitted.
Landolt, A. 1973, *A.J.*, **78**, 959.
Leech, K. J., Penston, M. V., Terlevich, R., Lawrence, A., Rowan-Robinson, M., and Crawford, J. 1989, *M.N.R.A.S.*, **240**, 349.
Leisawitz, D., and Hauser, M. 1989, *Ap. J.*, **332**, 954.
Lester, D. F., Harvey, P. M., and Carr, J. 1988, *Ap. J.*, **329**, 641.
Lonsdale, C. J., Helou, G., Good, J. C., and Rice, W. 1985, *Cataloged Galaxies and Quasars in the IRAS Survey* (Pasadena: JPL).
Maloney, P. 1990, in *The Interstellar Medium in Galaxies*, ed. H. A. Thronson and J. M. Shull (Dordrecht: Kluwer), p. 493.
Moorwood, A. F. M., Véron-Cetty, M.-P., and Glass, I. S. 1986, *Astr. Ap.*, **160**, 39.
Persson, C. J., and Helou, G. 1987, *Ap. J.*, **314**, 513.
Rice, W., Lonsdale, C. J., Soifer, B. T., Neugebauer, G., Koplan, E. L., Lloyd, L. A., de Jong, T., and Habing, H. J. 1988, *Ap. J. Suppl.*, **68**, 91.
Rieke, G. H. 1987, in *Star Formation in Galaxies*, ed. C. J. L. Persson (Pasadena: JPL), p. 633.
———. 1988, *Ap. J.* (*Letters*), **331**, L5.
Rieke, G. H., Cutri, R. M., Black, J. H., Kailey, W. F., McAlary, C. W., Lebofsky, M. J., and Elston, R. 1985, *Ap. J.*, **290**, 116.
Rowan-Robinson, M. 1990, in *The Interstellar Medium in Galaxies*, ed. H. A. Thronson and J. M. Shull (Dordrecht: Kluwer), p. 121.
Rowan-Robinson, M., and Crawford, J. 1989, *M.N.R.A.S.*, **238**, 523.
Sandage, A., and Tammann, G. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies* (Washington, DC: Carnegie Institution of Washington).
Sanders, D. B., and Mirabel, I. F. 1985, *Ap. J.* (*Letters*), **298**, L31.
Sanders, D. B., Scoville, N. Z., Young, J. S., Soifer, B. T., Schloerb, F. P., Rice, W. L., and Danielson, G. E. 1986, *Ap. J.* (*Letters*), **305**, L45.
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., and Scoville, N. Z. 1988, *Ap. J.*, **325**, 74.
Scoville, N. Z., Sanders, D. B., Sargent, A. I., Soifer, B. T., Scott, S. L., and Lo, K. Y. 1986, *Ap. J.* (*Letters*), **311**, L47.
Smith, C. H., Aitken, D., and Roche, P. F. 1989, *M.N.R.A.S.*, **241**, 425.
Smith, J., Gehrz, R. D., Grasdalen, G. L., Hackwell, J. A., and Dietz, R. D. 1988, *Ap. J.*, **329**, 107.
Soifer, B. T., Boehmer, L., Neugebauer, G., and Sanders, D. 1989, *A.J.*, **98**, 766.
Soifer, B. T., Sanders, D. B., Madore, B. F., Neugebauer, G., Danielson, G. E., Elias, J. H., Lonsdale, C. J., and Rice, W. L. 1987, *Ap. J.*, **320**, 238.
Solomon, P. M., Radford, S. J. E., and Downes, D. 1990, *Ap. J.* (*Letters*), **348**, 53.
Telesco, C. M., Decher, R., and Gatley, I. 1985, *Ap. J.*, **299**, 896.
Thronson, H. A., Bally, J., and Hacking, P. 1989, *A.J.*, **97**, 363.
Thronson, H. A., and Greenhouse, M. A. 1988, *Ap. J.*, **327**, 671.
Thronson, H. A., Majewski, S., Descartes, L., and Hereld, M. 1990, in *Astrophysics with Infrared Arrays*, ed. R. Elston (San Francisco: ASP), in press.
Thronson, H. A., Rubin, H., and Ksir, A. 1990, *M.N.R.A.S.*, submitted.
Thronson, H. A., and Telesco, C. M. 1986, *Ap. J.*, **311**, 98.
Thronson, H. A., Walker, C. K., Walker, C. E., and Maloney, P. 1987, *Ap. J.*, **318**, 645.
Thronson, H. A., Tacconi, L., Kenney, J., Greenhouse, M. A., Margulis, M., Tacconi-Garman, L., and Young, J. S. 1989, *Ap. J.*, **344**, 747.
Thuan, T. X. 1985, *Ap. J.*, **299**, 881.
Verter, F., and Rickard, L. J. 1989, *Astr. Ap.*, **225**, 27.
Wright, G. S., Joseph, R. D., and Meikle, W. P. S. 1984, *Nature*, **309**, 430.
Zasov, A. V., and Karachentsev, I. D. 1979, *Soviet Astr. Letters*, **5** (No. 3), 126.

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