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STAR FORMATION RATES IN RING GALAXIES FROM *IRAS* OBSERVATIONS

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ABSTRACT

We analyse *IRAS* and optical data for a sample of 26 ring galaxies and find: (1) relatively high average values of far-infrared luminosity $L_{\rm FIR}$, infrared to blue luminosity ratio $L_{\rm FIR}/L_B$, and color temperature compared to normal galaxies, implying a high recent star formation rate; (2) evidence that a large fraction of the young stars are located in the rings, indicating a very extended, coherent starburst; (3) a possible trend of the dispersion of $L_{\rm FIR}$ among rings as a function of ring diameter. Thus, within the uncertainties inherent in the study of this relatively small sample, it appears that ring galaxies represent a unique class of nonnuclear coherent starbursts.

Subject headings: galaxies: structure — infrared: sources — stars: formation

I. INTRODUCTION

There is growing evidence that the most extreme values of the global star formation rate in galaxies are found in tidally interacting and merging systems. Larson and Tinsley (1978) compared Arp (1966) galaxies with bridges and tails to "normal" Hubble atlas (Sandage 1961) galaxies and found that the former had a significantly larger dispersion in their *UBV* colors. This was interpreted, with the help of stellar population evolution models, as a dispersion in recent star formation rates (SFRs). High rates of star formation in a number of Arp interacting pairs were confirmed by Joseph *et al.* (1984), using observations in the infrared. The case for strongly enhanced star formation in the nuclear regions of spiral galaxies is further supported by Keel *et al.* (1985) for a sample of 161 galaxies with companions when compared with a control sample of noninteracting spirals. Bushouse (1986) has found that in most cases "violently interacting galaxies" have elevated Hα luminosities and equivalent widths compared with field galaxies. He notes, however, that such activity does not always accompany a strong interaction. The enhancement of star formation in a large fraction of interacting galaxies is also consistent with the *IRAS* observations of bright galaxies in the 10–100 μm range (Soifer *et al.* 1984).

Most work to date on interacting the starburst galaxies has focused on the SFRs in the nuclear regions of galaxies. However, there is additional evidence for the existence of enhanced star formation, and possible bursts, in extended regions (i.e., of size > 1 kpc) in galaxies. Examples include M51 and NGC 1068 (Telesco 1983). Among the most spectacular examples are the apparently ongoing mergers discussed by Joseph and Wright (1985, and references therein). In this paper we point out the existence of another, related class of extended starburst systems, the colliding ring galaxies (as interpreted by Lynds and Toomre 1976, Theys and Spiegel 1976, and Toomre 1978).

Evidence for high rates of star formation in several individual ring galaxies, derived from spectra and spectrophotometry, has been available for some time. The best studied examples include the Cartwheel galaxy (A0035, see Fosbury and Hawarden 1977, hereafter FH), the Lindsey-Shapley ring (AM 064, see Few, Madore and Arp 1982), and the Vela ring (Taylor and Atherton 1984). Theys and Spiegel (1976) were well aware that the rings in their sample were generally blue and often exhibited low-excitation emission lines. They appear to favor the interpretation that the measured colors were due to a burst of age greater than 10^8 yr. In §§ II and III we assemble a somewhat larger sample of ring galaxies and use published velocities and *IRAS* observations to estimate the infrared luminosities $L_{\rm FIR}$ and the infrared to blue luminosity ratios $L_{\rm FIR}/L_B$ of the sample galaxies. The relatively high values of $L_{\rm FIR}$, $L_{\rm FIR}/L_B$ and far-infrared color temperature confirm the suggestion that ring galaxies are primarily collisionally induced objects, having much in common with other interacting or colliding systems. Indeed, if most of the star formation occurs in the ring, as discussed in § III, then ring galaxies represent a unique class of nonnuclear coherent starbursts.

II. THE DATA SAMPLE

The sample of ring galaxies we have assembled for this study is listed in Table 1. Most of these rings are well-known systems from the primary and secondary lists of Theys and Spiegel (1976). We have also included a number of galaxies from the Arp and Madore (1986, hereafter AM) list of southern peculiar galaxies. The AM list is potentially a very rich source of ring galaxies. However, care must be exercised in using it, since the word "ring" used to describe a variety of different types of system. Specifically, it is not restricted to those that appear to be the result of a nearly head-on collision between a galaxy with a cold (disk) component and an arbitrary companion, which are the systems we are interested in here. Few and Madore (1986) have compiled and analysed a subset of the AM galaxies which appear to be true colliding ring galaxies. Most of the additional galaxies included in Table 1, beyond the Theys and Spiegel list, are Few and Madore galaxies for which published velocities are available.

Most of the ring galaxies in this sample are relatively well defined "crisp" rings. However, as the referee has pointed out to us, there exists some possibility of contamination of the sample by galaxies which may have formed rings by a process other than a galaxy collision. A possible example of such contamination is NGC 2381, which may be a barred galaxy with a "pseudo-ring" (Buta 1984; Athanassoula and Bosma 1985). We hope that the level of contamination of our sample is small.

Ultimately, the only reliable way of distinguishing between a

TABLE 1

THE SAMPLE

NAME[a] (1)	α(1950) (2)	δ(1950) (3)	$V_{\rm helio}$ (km s^{-1}) (4)	V_0 (km s^{-1}) (5)	REFERENCE (6)	$m_{\rm pg}$[b] (mag) (7)	B_T[c] (mag) (8)	DIAMETER (major × minor) (9)	*IRAS* DATA 60 μm (10)	 100 μm (11)	 log (FIR) (12)
N7828/9 = Arp 144	$00^{\rm h}03^{\rm m}.8$	$-13°41'$	5800	5888	1	...	...	37".9 × 15".2	2.03	3.53	-12.95
A0004 − 06 = Arp 146	00 04.17	−06 54.9	22615	22732	2	...	...	18.3 × 11.1	≤0.5	≤1.0	≤ −13.54
A0035 − 339 = Cartwheel	00 35.23	−33 59.4	8934	8914	3	15.2	14.8[d]	74 × 60	0.65	1.54	−13.39
AM 0113 − 324	01 13.57	−32 44.6	6041	6003	4	...	...	80 × ...	≤0.5	≤1.0	≤ −13.54
A0220 + 41A/B = Arp 145	02 20.06	+41 8.6	5178	5357	2	14.1	14.3_c	63.2 × 48.1	0.82	1.75	−13.31
N985 = Mrk 1048	02 32.19	−09 0.3	12950	12948	1	...	14.1	35 × ...	1.43	1.91	−13.15
N1143/4 = Arp 118	02 52.06	−00 23	8465	8478	5	13.2	14.5	36.5 × 20.3	5.23	11.21	−12.50
IC 298A/B = Arp 147	03 08.7	+01 08	9655	9660	6	15.1	15.7_c	16.3 × 14.2	0.97[e]	1.83	−13.25
A0459 + 03 = II Zw 28	04 59	+03 30	8649	8572	1	...	15.58	14 × ...	≤0.5	≤1.0	≤ −13.54
AM 0608 − 752 = IC 2164	06 08.56	−75 21.3	10790	10539	7	14.0	...	...	0.40	1.54	−13.49
AM 064 − 741 = E34–IG 11	06 44.36	−74 11.45	6611	6351	8	...	15.1	95 × 50	1.42	4.03	−13.01
A0708 + 73 = Arp 141A/B	07 08.2	+73 34	2709	2874	9	14.22	14.47_c	75.9 × 40	≤0.5	≤1.0	≤ −13.54
AM 0719 − 625 = N2381	07 19.48	−62 58.2	3060	2781	7	...	...	74 × ...	[0.60]	1.48	−13.41
N2444/5 = Arp 143	07 43.6	+39 8.2	4020	4017	9	13.1	13.60	84.5 × 67.6	3.34	6.08	−12.73
A0855 + 37 = II Hz 4	08 55.3	+37 16	12885	12862	6	...	...	29 × ...	≤0.5	≤1.0	≤ −13.54
N2793	09 13.71	+34 38.5	1681	1644	10	13.9	14.2_c	56 × ...	0.83	1.66	−13.32
N2936/7 = Arp 142	09 35.1	+02 58	6981	6794	1	14.4	13.95	81 × 61	2.11	4.84	−12.88
AM 1006 − 380 = Vela Ring	10 06.91	−38 9.7	4845	4555	6	13.5	...	70 × ...	1.06	3.51	−13.10
A1040 + 13 = Arp 291	10 40.16	+13 43.2	1210	1084	10	13.8	14.3_c	58 × 33	0.56	1.2[e]	−13.47
A1101 + 41 = Arp 148	11 01.10	+41 7.2	10350	10363	1	...	15.05	20.3 × 14.2	5.97	10.26	−12.49
A1229 + 66 = VII Zw 466	12 29.8	+66 40	14494	14341	2	...	...	22 × ...	≤0.5	≤1.0	≤ −13.54
A1238 + 16 = Arp 149 = IC 803A/B	12 37.02	+16 52.0	7985	7932	2	15.3	15.4_c	30.4 × ...	0.66[e]	1.3	−13.42
N4774A/B = I Zw 45	12 50.8	+37 5	8271	8314	2	14.6	14.85	23 × ...	1.54	3.35	−13.03
N5410 = VV 256	13 58.81	+41 14	3685	3785	1	14.1	14.4_c	60 × ...	0.79	1.82	−13.31
N5544/5 = Arp 199	14 14.99	+36 48.37	3207	3302	1	13.2	13.6_c	67 × 67	0.64	2.03	−13.33
AM 1434 − 783 = IC 4448	14 34.36	−78 35.7	4580	4355	11	14.6	...	...	2.30	4.85	−12.86

[a] N, NGC; AM, Arp and Madore 1986.

[b] From Zwicky *et al.* 1961.

[c] From RC2; subscript *c* indicates corrected magnitude (see text).

[d] Fosbury and Hawarden 1977.

[e] Moderate quality flux.

REFERENCES.—(1) de Vaucouleurs *et al.* 1976. (2) de Vaucouleurs *et al.* 1979. (3) Mebold *et al.* 1977. (4) Rubin *et al.* 1976. (5) Huchra *et al.* 1983. (6) Theys and Spiegel 1976. (7) Fairall 1980. (8) Few *et al.* 1982. (9) Shostak 1978. (10) Silverglate and Krumm 1978. (11) Sersic *et al.* 1979.

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collision product and a psuedo-ring will be through a careful study of the dynamics of the ring propagation. The existence of a strong rarefaction behind the expanding ring may be one such diagnostic (Appleton and Struck-Marcell 1987).

The 26 galaxies included in the present study do not in any sense represent a statistically complete sample. It would be very difficult to determine the selection effects embodied in the Theys and Spiegel or the AM lists. One obvious selection effect is that face-on ring galaxies are presumably more likely to be included in such lists. However, apart from reducing the number of ring-galaxy candidates, the exclusion of many edge-on ring galaxies should not affect the conclusions we draw from our sample. In addition to this selection effect, we have imposed the requirement that the galaxy have a published recession velocity. While the statistical incompleteness of our sample renders our conclusions tentative, ongoing redshift surveys should improve the situation within a few years.

In Table 1 we list the names of the sample ring galaxies and their coordinates (cols. [2] and [3]; derived mainly from de Vaucouleurs, de Vaucouleurs and Corwin 1976, hereafter RC2, or from AM). Also given in Table 1 are both the helicentric and local group velocities[1] (cols. [4] and [5]) and the source of these data (col. [6]). Photographic magnitudes and blue magnitudes B_T are also presented (cols. [7] and [8]). In many cases B_T was not directly available, so we have converted the Zwicky magnitudes using the surface brightness–related conversion factors of Auman, Hickson, and Fahlman (1982). Although this conversion is bound to lead to some uncertainty (see Giovanelli and Haynes 1984), we believe that it is the most appropriate for our sample. These corrected Zwicky magnitudes are tabulated in column (8) but are subscripted to distinguish them from the directly measured values. The angular diameter of the dominant ring for each ring galaxy is also given in Table 1 (col. [9]). Most of these were measured from the Arp (1966) atlas or, for two of the AM rings, from the ESO transparencies. In other cases, the diameters come from Theys and Spiegel (1976).

The last three columns of Table 1 tabulate the infrared data taken from the *IRAS* Point Source Catalog (Lonsdale *et al.* 1985). The 60 μm and 100 μm fluxes are presented, and also the quantity log (FIR). As described by Lonsdale *et al.*, FIR is a measure of the integrated infrared flux from the source. It is often referred to as the 80 μm flux, since it is equivalent to the flux collected in a detector with a bandwidth of 80 μm centered on 82.5 μm. In all cases the positional agreement between the *IRAS* source and the ring galaxy is very good, and so we believe that the probability of a mistaken identification is low. In addition, the ring galaxies are in general smaller than 1′, so the values for the far-infrared fluxes are unlikely to be underestimated due to beam dilution at both 60 and 100 μm.

Of the 26 ring galaxies in the sample, 20 are detected by *IRAS*. We have assumed that for the nondetections the approximate upper limits to the fluxes at 60 and 100 μm are 0.5 Jy or less and 1.0 Jy or less respectively. According to the definition of FIR, this would correspond to an upper limit to the integrated flux of $\log(\mathrm{FIR}) \leq -13.54$.

The far-infrared luminosity L_{FIR} is given for the ring galaxies in column (2) of Table 2 (Lonsdale *et al.* 1985). The values are valid for dust temperatures in the range 20–80 K and dust emissivity indices n between 0 and 2 (we assume emissivity is proportional to ν^{+n}, where ν is the frequency). In order to make an approximate estimate of the bolometric flux from the source, we also give the color-corrected luminosity $L_{\mathrm{FIR}}{}^*$

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[1] We assume $V_0 = V_\odot + 300 \sin(l) \cos(b)$.

TABLE 2

LUMINOSITIES

Galaxy (1)	$\log\left(\frac{L_{\mathrm{FIR}}}{L_\odot}\right)$ (2)	$\log\left(\frac{L_{\mathrm{FIR}}{}^*}{L_\odot}\right)$ (3)	$\log\left(\frac{L_B}{L_\odot}\right)$ (4)	$\frac{L_{\mathrm{FIR}}}{L_B}$ (5)	$\frac{L_{\mathrm{FIR}}{}^*}{L_B}$ (6)	D_{LIN} (kpc) (7)
Arp 144	10.04	10.18	...	...	...	10.8
Arp 146	≤10.64	≤10.79	...	...	...	20.2
A0035−339	9.98	10.14	10.14	0.69	1.0	31.9
AM 0113−324	≤9.48	≤9.63	...	...	...	23.3
Arp 145	9.61	9.78	10.10	0.32	0.48	16.4
N985	10.54	10.68	10.83	0.51	0.71	22.0
Arp 118	10.82	10.98	10.34	3.02	4.4	15.0
Arp 147	10.18	10.33	9.98	1.60	2.2	7.6
II Zw 28	≤9.79	≤9.94	10.05	≤0.55	≤0.78	5.8
AM 0608−752	10.02	10.26	...	...	...	...
AM 064−741	10.06	10.25	...	...	...	29.3
Arp 141	≤8.84	≤8.99	9.47	≤0.23	≤0.33	10.6
AM 0719−625	[8.95][a]	[9.12][a]	...	...	...	10.0
Arp 143	9.94	10.09	10.07	0.74	1.0	16.5
II Hz 4	≤10.15	≤10.30	...	...	...	18.1
N2793	8.58	8.73	9.02	0.36	0.51	4.5
Arp 142	10.25	10.41	10.37	0.76	1.1	26.7
AM 1006 (Vela)	9.68	9.91	...	...	...	15.5
Arp 291	8.07	8.23	8.68	0.25	0.35	3.0
Arp 148	11.00	11.15	10.25	5.62	7.9	10.2
VII Zw 466	≤10.24	≤10.39	...	...	...	15.3
Arp 149	9.85	10.00	9.87	0.95	1.35	11.7
I Zw 45	10.28	10.44	10.14	1.38	2.00	9.3
N5410	9.31	9.47	9.63	0.48	0.69	11.0
Arp 199	9.17	9.38	9.84	0.21	0.35	10.7
AM 1434−783	9.88	10.04	...	...	...	...

[a] Not detected at 60 μm.

assuming $n = 1$ in column (3) (see Lonsdale *et al.* 1985). Since this requires assumptions about the shape of the spectrum longward of 100 μm, this luminosity should be treated as a guide to the total far-infrared luminosity being radiated by the sources. As emphasized strongly by Lonsdale *et al.*, although this correction yields reasonable agreement for galaxies in which the full infrared spectrum has been measured, the numbers of such galaxies are still small. This is the reason both $L_{\rm FIR}$ and $L_{\rm FIR}{}^*$ are given in Table 2. In addition to the infrared luminosity, we also present the blue luminosity L_B in column (4). We emphasize that, unlike much of the *IRAS* data published on galaxies, we assume a value for the Hubble constant of 100 km s^{-1} Mpc^{-1}. The blue luminosities were derived from B_T after correction for Galactic absorption following RC2 but are uncorrected for internal absorption. Apart from the considerable uncertainty about what internal absorption correction would be appropriate for ring galaxies, most of the rings are relatively face-on, so such a correction is unlikely to be significant. Ratios of $L_{\rm FIR}$ and $L_{\rm FIR}{}^*$ to L_B are also presented (cols. [5] and [6]), and finally the linear diameters of the rings (col. [7]). For the unusual object VII Zw 466, the linear diameter presented here may be the semidiameter, if the interpretation of Freeman and de Vaucouleurs (1974) is correct.

III. RESULTS AND DISCUSSION

The distribution of far-infrared luminosities $L_{\rm FIR}$ for the ring galaxies shows considerable dispersion, as can be seen in Figure 1. However, the majority of the well-studied galaxies (e.g., Theys and Spiegel's 1976 primary group) lie within the main peak of the distribution at around $10^{10}\,(100/H_0)^2\,L_\odot$. To compare the luminosities of the rings with a sample of more normal galaxies, we plot in Figure 1 the average values of log ($L_{\rm FIR}$) (and their mean errors) for the sample of Shapley-Ames galaxies described by De Jong *et al.* (1984). Their luminosities have been adjusted downward by a factor of 4 to make them consistent with $H_0 = 100$. It is clear from Figure 1 that the main peak in the ring galaxy distribution is significantly in excess of the mean derived by De Jong *et al.* (1984) for even the most luminous class of the Shapley-Ames galaxies (the barred spirals). The average value of $L_{\rm FIR}$ determined for the rings (excluding the unusually high value of $L_{\rm FIR} = 1.0 \times 10^{11}\,L_\odot$ of Arp 148; see below) is $1.2 \times 10^{10}\,L_\odot$. This value is between 2 and 6 times the average for most galaxy types in the Shapley-Ames sample.

Well-known "classical" rings such as A0035 (Cartwheel), AM 064 − 741 (Lindsey-Shapley ring) and I Zw 45 have luminosities clustered around the peak, although a few objects extend the distribution upward by a factor of 10 (NGC 985, Arp 118, and Arp 148). To attempt to put these objects in context, we have also plotted the values of $L_{\rm FIR}$ for M82 (the prototype "starburst" galaxy) at an assumed distance of 3.25 Mpc (Tammann and Sandage 1968) and NGC 6240 (defined as a "super-starburst" by Joseph *et al.* 1984). We emphasize that these latter two fluxes are not the bolometric fluxes but are the values of $L_{\rm FIR}$ determined from the *IRAS* point-source catalog. We note that M82 is also detected as an extended source (see

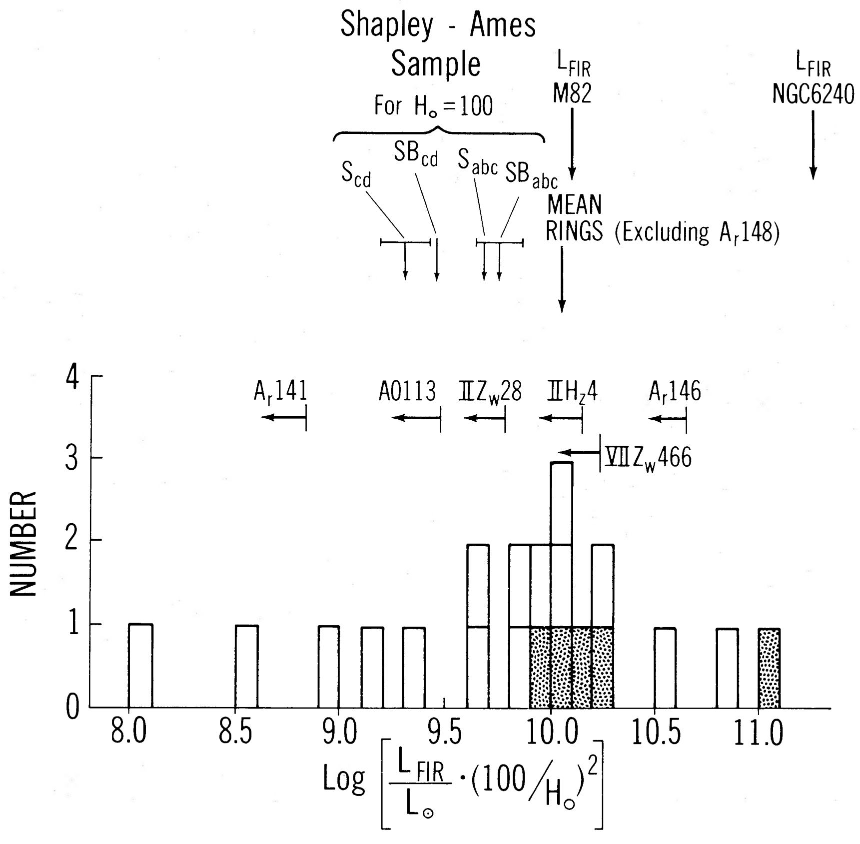

FIG. 1.—Distribution of far-infrared luminosities $L_{\rm FIR}$ (uncorrected for color; see text) for the ring galaxy sample. *Stippled boxes*, galaxies in the "primary" list of Theys and Spiegel (1976). *Horizontal arrows*, upper limits (see text). *Vertical arrows*, mean luminosities and mean errors for galaxies in various classes from the Shapley-Ames sample of de Jong *et al.* (1984) and the *IRAS* point-source luminosities for the starburst galaxies M82 and NGC 6240. The mean value of $L_{\rm FIR}$ for our ring galaxy sample (excluding the very luminous galaxy Arp 148) is also shown.

Helou and Walker 1986), and an additional large-scale flux has not been taken into account in this value for $L_{\rm FIR}$. It is clear from these comparisons that 4–5 ring galaxies lie in the range of infrared luminosities frequently attributed to starburst activity.

It has been known for some time (see, e.g., Keel *et al.* 1985) that the median blue luminosity of Arp interacting galaxies (excluding rings for the most part) is 0.5 mag brighter than that of noninteracting galaxies. This elevated luminosity appears to be reflected in our ring galaxy sample. The mean value of $L_B = 1.4 \times 10^{10}\ (100/H_0)^2\ L_\odot$ for the ring galaxies is in complete accord with the value derived by Keel *et al.* for Arp interacting galaxies in general. An explanation of this enhancement in terms of enhanced levels of star formation is strongly supported in the ring galaxy case by the unusually high infrared emission.

Since the values of both infrared and blue luminosities in ring galaxies are apparently elevated relative to more normal galaxies, it is not surprising that the ratio $L_{\rm FIR}/L_B$ is not excessively high for the majority of the ring galaxies (exceptions include Arp 118 and Arp 148). However, even excluding Arp 148, the average value of $L_{\rm FIR}/L_B = 0.86$ is a factor of 2 larger than the average of 0.40 for the Shapley-Ames sample of De Jong *et al.* (1984). After color correction, the infrared to optical luminosity ratio $L_{\rm FIR}{}^*/L_B$ is on average 1.0 with a substantial spread to both higher ($L_{\rm FIR}{}^*/L_B = 7.9$ for Arp 148) and lower ($L_{\rm FIR}{}^*/L_B < 0.33$ for Arp 141) values. As a general rule then, ring galaxies, such as the Cartwheel, emit as much infrared radiation as blue optical light.

De Jong *et al.* (1984) describe an approximate correlation between the infrared to blue luminosity ratio $L_{\rm FIR}/L_B$ and the color temperature T_c. In general, galaxies with higher values of $L_{\rm FIR}/L_B$ have larger color temperatures. De Jong *et al.* interpret the increase in $L_{\rm FIR}/L_B$ with T_c as an indication of enhanced star formation. OB stars surrounded by dust in H II regions would add a hot component to the normal cool diffuse galactic dust component, giving rise to a decrease in the ratio of $S(100\ \mu{\rm m})/S(60\ \mu{\rm m})$.

In Figure 2 we plot the values of log ($L_{\rm FIR}/L_B$) against log (S_{100}/S_{60}) for the ring galaxies (*filled circles*) and the complete Shapley-Ames sample of De Jong *et al.* (1984; *open circles*). It is strikingly evident that the ring galaxies populate the upper right-hand portion of the diagram, forming a continuous extension of the correlation found by De Jong *et al.* This supports the view that the infrared luminosity of rings is dominated by radiation from OB stars. Objects such as Arp 148 and Arp 118 are seen to be unusually strong infrared emitters and lie near the top of Figure 2. Arp 148 has been recognized for some time to be an unusual object, and observations by Joy and Harvey (1986) show that it emits much of its 10 μm flux in the nucleus, probably from the optical and near-infrared plume, which extends perpendicularly from the disk.

Another object which occupies an unusual position in Figure 2 is NGC 985 (= Mrk 1048). This galaxy is known to be a Seyfert galaxy and a strong emitter of X-rays (Ghigo, Wardle, and Cohen 1983). Its infrared spectrum is flatter than the other ring galaxies, probably indicating a substantial nonthermal component.

In contrast to most of our ring galaxy sample, Arp 199 has IR characteristics more in keeping with those of normal galaxies. It has the steepest infrared spectrum of all the objects studied ($S_{100}/S_{60} = 3.17$) and lies at the lower edge of the distribution of Shapley-Ames galaxies (see Fig. 2). It is notable that this galaxy was one of the few ring galaxies studied by Keel *et al.* (1985), and they found that it exhibits the characteristics of a low-ionization nuclear emission-line region on the basis of unusually strong [N II] λ6583 line emission from its nucleus.

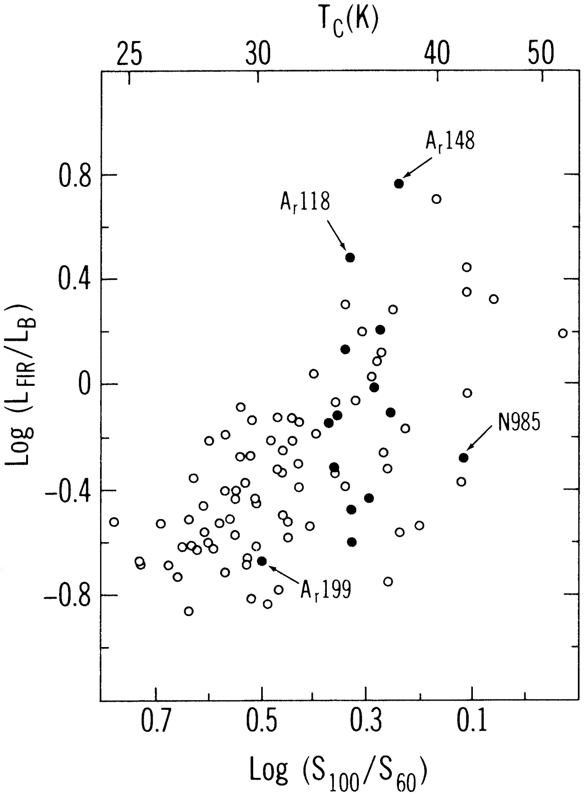

FIG. 2.—Logarithmic values of far-infrared to blue luminosity ratio of the rings vs. color temperature T_c (*upper axis*) or the ratio of the 100 μm to 60 μm *IRAS* flux. *Filled circles*, ring galaxies; *open circles*, galaxies from the Shapley-Ames sample of de Jong *et al.* (1984).

The evidence that we have presented so far strongly suggests that ring galaxies are actively giving birth to a large and (in most cases) dominant population of young OB stars. It is important to try to determine whether the emission originates primarily from the ring component or, as is frequently the case in starburst galaxies, from the nuclear region. However, the *IRAS* observations do not provide adequate spatial resolution to distinguish between these possibilities. An exception is perhaps the optically empty ring Arp 147. However, even in this case, the detection of IR emission from Arp 147 (IC 298A) cannot be unambiguously assigned to the ring because of the close proximity of its companion IC 298B. Although this companion is an early-type galaxy ($T = -2$; RC2), it is confused within the *IRAS* beam with IC 298A and therefore could conceivably contribute to the IR flux from the ring galaxy.

Perhaps a less ambiguous case is that of A0035 (Cartwheel). This galaxy and its dwarf companions were the subject of a detailed study by FH. The object is dominated by a very luminous outer ring of giant H II regions but contains two inner knots, within the ring, which form an offset nucleus, and also a faint inner ring. Two possible small companions lie along the minor axis of the galaxy (objects 3 and 4 of Plate 1 in FH), one of which is presumed to be the intruder which caused the ring formation (Davies and Morton 1982). Spectrophotometric scans made by FH show that the *outer luminous ring alone* exhibits emission lines. No emission lines were detected interior to the outer ring. The possibility that star-forming regions are hidden within a heavily obscured nucleus would seem unlikely, since strong stellar absorption lines characteristic of an old population of stars are detected there.

Apart from the obvious identification of the source of the infrared radiation with the bright outer ring in the Cartwheel, the only remaining alternative is the nucleus of one of the companions. Galaxy 3 is an early-type galaxy in which FH found no evidence for emission-line gas. Galaxy 4 is a possible source of the IR, since emission lines were detected from it. However, if most of the far-infrared emission we see from the Cartwheel originated in this low-luminosity galaxy ($L_B = 4.7 \times 10^8 L_\odot$ for $H_0 = 100$ km s^{-1} Mpc^{-1}), then it would have an unusually high value of $L_{\rm FIR}{}^*/L_B = 24$ (!), rivaling the most luminous of the super-starburst galaxies. This extreme value is not consistent with the description of it by FH as a galaxy with "rather normal undisturbed spiral structure." It would appear that, in the Cartwheel galaxy, we have an unambiguous indication of strong star formation in the outer ring only.

If we assume that the majority of the FIR emission from A0035 comes from dust heated by a population of O stars ($M = 10\ M_\odot$, $L = 10^4\ L_\odot$), then the infrared luminosity of $L_{\rm FIR}{}^* = 1.4 \times 10^{10}(100/H_0)^2\ L_\odot$ would indicate the existence of 1.4×10^6 O-type stars in the ring. This number compares favorably with the independent estimate of the Lyman continuum flux in the ring by FH. Adjusting their figures to $H_0 = 100$, their observations suggest 10^5 O6 stars are required to provide the observed Hβ luminosity found in the ring. FH argue that this is probably an underestimate, since only the hottest stars contribute strongly to the Lyman continuum. Given the high integrated blue luminosity of the ring, they estimate that as many as $1.08 \times 10^6\ (100/H_0)^2$ O-stars would be required to account for this luminosity. The good agreement between their estimate and ours derived from the infrared data argues in favor of the ring being the primary source of the far-infrared flux. The high supernova rate implied by this result could easily account for the patchy, clumpy optical appearance of the ring, uncovering some H II regions, but leading others obscured and only visible in the infrared.

Two other rings have been the object of detailed optical studies. Few, Madore, and Arp (1982) obtained spectra that included 30 emission knots in AM 064−741 (Lindsey-Shapley ring). Although their study focused on kinematics, rather than emission-line strengths, it seems clear that the strongest emission originates in the ring rather than the nucleus. Also, studies of the Vela galaxy (=AM 1006−38 [Sersic's ring]) by Dennefeld, Laustsen, and Materne (1979) and Taylor and Atherton (1984) show strong emission lines associated with two inner rings contained in a central bulge and somewhat weaker emission lines from the outer rings. Few or no emission lines are found associated with the nucleus.

Although we cannot rule out important contributions to the IR flux from nearby companions or inner nuclei in all cases, we assume in what follows that the optically dominant rings are the principal sites of star formation in the ring galaxies, by analogy with A0035. The relatively high color temperatures of the dust in the rings indicated in Figure 2 and the higher than average values of $L_{\rm FIR}/L_B$ support this conclusion. The *IRAS*

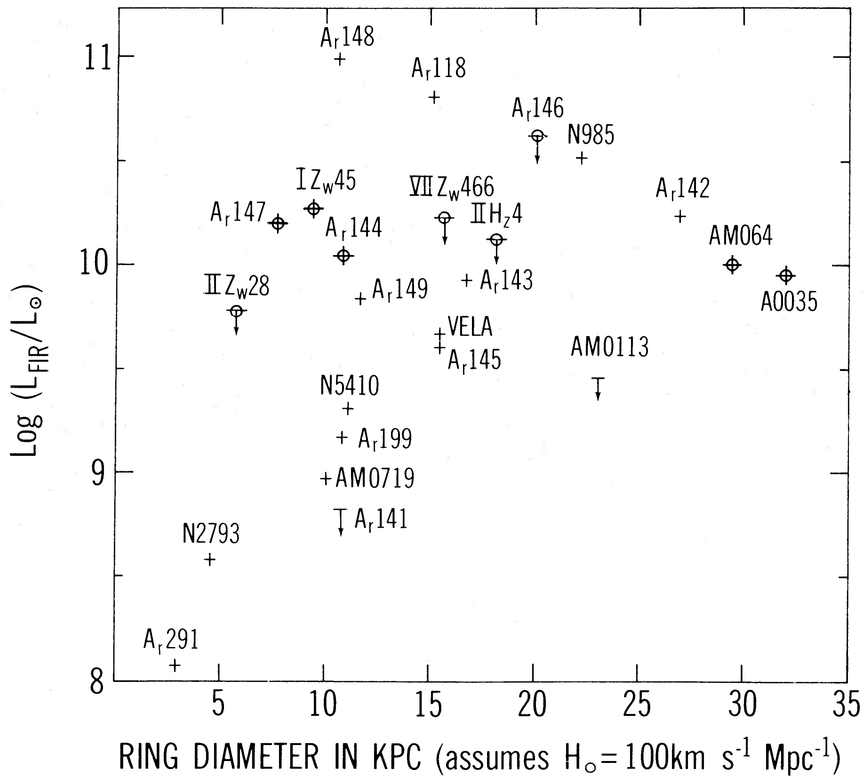

FIG. 3.—Logarithm of far-infrared luminosity vs. linear diameter of the dominant ring in the ring systems. *Pluses*, *IRAS* detection; *vertical arrows*, upper limits. Ring galaxies in the "primary" list of Theys and Spiegel (1976) are circled.

results therefore confirm the view, held by Lynds and Toomre (1976) and Theys and Spiegel (1976), that most ring galaxies are the products of collisions.

It is interesting to investigate whether the current star formation rate, as indicated by L_{IR}, in ring galaxies is a function of ring diameter. Such an effect may be expected as the density wave expands through a gas-rich disk in the collisional model of Lynds and Toomre (1976) or Theys and Spiegel (1976). We plot in Figure 3 the linear diameter of the ring versus log (L_{FIR}). With the exception of Arp 148 and Arp 118, there is a surprising tendency for the FIR luminosity to be independent of linear ring diameter, in the range $9.8 \leq \log (L_{\mathrm{FIR}}/L_{\odot}) \leq 10.4$. (A linear regression including all detected galaxies has a slope of 0.04, with a correlation coefficient of 0.45.) This characteristic is especially noticeable for the well-classified ring galaxies (i.e., those in Theys and Spiegel's primary list). If the whole sample is included it appears that smaller rings with $D < 12(100/H_0)$ kpc have a wider spread in FIR than the larger rings. This may be an indication either that objects such as NGC 2793 and NGC 5410 are not collisionally formed ring galaxies, or it may be evidence for some self-regulating mechanism in the star formation process in rings, which leads to a maximum saturated level of star formation that is usually reached when the ring is large and presumably well evolved. Such self-regulation is in fact found to occur in recent cloud fluid models of ring galaxies (Appleton and Struck-Marcell 1987).

IV. CONCLUSIONS

Our analysis of *IRAS* and optical data on ring galaxies has led to the following main results. First, we find that the average values of far-infrared luminosity L_{FIR}, L_{FIR}/L_B, and color temparature T_c are significantly greater than in normal galaxies. Indeed, the average value of L_{FIR} for the ring sample is comparable to that of the well-known nuclear starburst galaxy M82. Second, although the low resolution of the *IRAS* observations does not allow a direct determination of the spatial distribution of star formation in the sample galaxies, detailed optical studies do imply that in several individual cases a large population of young stars is located in the ring. Thus, the optical and IR together indicate a very extended starburst phenomenon, i.e., one which maintains coherence on the scale of a typical ring diameter, ~10–20 $(100/H_0)$ kpc. The third result is that the infrared luminosity of the ring galaxies is nearly constant ($L_{\mathrm{FIR}} = 10^{10}\ L_{\odot}$) to within a factor of 3 over a range of diameters $10 \leq D \leq 30$ kpc ($H_0 = 100$). It appears that the smaller rings ($D < 12$ kpc) have a larger spread in infrared luminosities than the larger ones. This latter result must be treated with some caution because of the small number of points plotted in Figure 3.

Given the small sample, these results are tentative, but the situation is likely to improve considerably in the near future. First, the acquisition of radial velocities for the ring galaxies in the Arp and Madore catalog would add a few galaxies with *IRAS* detections and many interesting *IRAS* upper limits to Figures 1–3. Furthermore, it seems clear that if most of the galaxies with upper limits in Figure 1 have IR luminosities near the peak of those detected, even a modest improvement in far-infrared sensitivity (compared with *IRAS*) will yield more detections. At the same time, detailed optical and near-IR studies of the spatial distribution of colors and emission lines would also be extremely helpful in determining the distribution of star formation and the old stellar population in ring galaxies. Similarly, radio continuum observations would provide complementary information on the distribution of star formation, and 21 cm data would allow an estimate of density wave amplitude in the gas.

The relative simplicity of the expanding density wave phenomenon in collisional ring galaxies, compared, for example, with the often complicated phenomena which can accompany star formation in spiral arms (cf. Elmegreen 1985), make ring galaxies among the most attractive objects for the study of star-formation processes. We have begun a program of numerical cloud fluid modeling of the star formation and gas dynamics in the disks of ring galaxies (Appleton, Struck-Marcell, and Foster 1985). More extensive work will be presented elsewhere (Appleton and Struck-Marcell 1987; Struck-Marcell and Appleton 1987), but when certain conditions in the interstellar medium prevail, we note that starbursts can occur within the ring, accompanied by a suppression of star formation behind (i.e., inside) the ring. These model bursts typically yield a net increase of SFR by a factor of ~2–3. The rings are clearly very exceptional galaxies. However, this does not imply that they are peripheral to the study of star formation in galaxies. Indeed, it now appears that ring galaxies provide both an outstanding example of extended coherent starbursts and a laboratory for the study of the effects of large-scale, nonlinear density waves on the interstellar gas.

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Note added in proof.—Following the submission of this paper, Dr. Norbert Jeske kindly sent us a copy of his Ph.D. thesis (University of California, Berkeley [1986]), in which he presents new radio continuum data, 21 cm line data, optical spectroscopy, and imagery for a sample of ring galaxies substantially overlapping the present one. Jeske's conclusions regarding enhanced star formation in rings, based on these data and his own analysis of the *IRAS* data for his sample, agree with ours. We have also learned of another investigation of the *IRAS* properties of ring galaxies by Dr. Ken-Ichi Wakamatsu (private communication), which also yields results in accord with ours.

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