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INFRARED EMISSION AND STAR FORMATION IN EARLY-TYPE GALAXIES

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ABSTRACT

We have used *Infrared Astronomical Satellite* data for elliptical and S0 galaxies in an effort to determine whether star formation is taking place in galaxies that are often thought to be inert. We used *IRAS* two-color diagrams to interpret galaxian infrared colors. We conclude that such diagrams are often ambiguous in determining whether or not emission arising from star formation dominates far-infrared luminosity. Perhaps 2/3 of our small sample have mid- and far-infrared colors that are characteristic of "infrared cirrus," emission from dust that is mixed with the general interstellar medium and not directly part of star-forming regions. However, the remaining one-third have infrared colors that are consistent with emission from dusty regions surrounding young stars. Star formation rates in the range 0.1–1 $M_\odot$ yr^{-1} are estimated for some normal elliptical galaxies, although with significant systematic uncertainty. In general, star-formation rates that we calculate for these objects are roughly comparable to the mass-loss rate for evolved stars, but we point out that other evidence suggests that mergers or gas infall play a more important role in fueling creation of stars. Furthermore, "active" nuclei may contribute significantly to the infrared emission in some objects.

Subject headings: galaxies: general — galaxies: photometry — infrared: spectra — stars: formation

I. INTRODUCTION

There is no reason to completely exclude early-type galaxies—those classified as ellipticals or S0's—from the class of active star-forming galaxies. As Tinsley (1980) noted, a major difference between the formation of stars in spiral and nonspiral galaxies may be the obvious presence of luminous blue stars in the former. Without such stars, and giant emission nebulae, elliptical and S0 galaxies have been consigned to the dustbin of inert objects. More detailed investigation, however, has not excluded the possibility of ongoing low-mass star formation in these systems.

Recently, there have been extensive observations of early-type galaxies that indicated that star formation is likely to be taking place in these objects at some level. Emission of 21 cm H I and $J = 1 \rightarrow 0$ CO have been studied (e.g., Knapp, Turner, and Cunniffe 1985; Wardle and Knapp 1986; Wiklund and Rydbeck 1986; Thronson and Bally 1987), as has radio continuum emission (e.g., Sadler 1984; Demoulin-Ulrich, Butcher, and Boksenberg 1984). Increasingly sophisticated work at visual and ultraviolet wavelengths has resulted in models for early-type galaxies in which young stars may make a modest contribution to "excess" blue light observed in many objects (e.g., Gunn, Stryker, and Tinsley 1981; Rose 1985; Véron and Véron-Cetty 1985; Rocca-Volmerange and Guiderdoni 1987). Some of the most interesting studies of these galaxies have been those of Jura (1986) and Jura *et al.* (1987) who discussed emission observed by the *Infrared Astronomical Satellite* (*IRAS*). A recent review of much of our current knowledge about the interstellar medium (ISM) in ellipticals is presented by Schweizer (1987).

Interpretation of the large-scale infrared emission from galaxies is seriously complicated by lack of knowledge about the location of the dust. Cox, Krügel, and Mezger (1986), Cox and Mezger (1987), Persson and Helou (1987), de Jong and Brink (1987), and Rowan-Robinson (1987) have all discussed the various components that contribute to the infrared emission from the Milky Way and other galaxies and have emphasized the difficulties in extracting information about particular galaxian components. The two components that most concern us here are "infrared cirrus," dust that is part of the general non–star-forming diffuse interstellar medium, and dust associated with young star forming regions. Persson and Helou, in particular, have emphasized that the "cirrus" might contribute a great deal to the observed far-infrared luminosity, leading to a mistaken belief that an object is actively forming stars. A third probable component that might contribute to the far-infrared emission is a Seyfert-like nucleus, considered in some detail by Rowan-Robinson.

A major step in deconvolving the contributions from "cirrus" and from dust associated with young stars was taken by Helou (1986). He showed that infrared colors of normal galaxies are widely distributed in a plot of $\log[F_{60}/F_{100}]$ versus $\log[F_{12}/F_{25}]$, where F_λ is the flux density in the *IRAS* bands. Interpretation of this distribution may be straightforward: "infrared cirrus" has different colors from that of dust associated with young stars. Thus, different combinations of these two components will cause an object to appear in different locations in a color-color plot.

We have been studying the molecular line and infrared emission from dwarf galaxies (Thronson and Telesco 1986; Thronson and Bally 1987; Thronson, Bally, and Hacking 1987). Although early-type dwarfs are infrequently detected by *IRAS* (see also Jura 1986), we are impressed by the range of infrared colors that the objects show, as wide a range as that found for the more active late-type giant galaxies. We take this opportunity to present preliminary results of our study of infrared emission from early-type galaxies, with an emphasis on formation of stars.

II. THE DATA AND TECHNIQUES OF ANALYSIS

Only a modest number of early-type galaxies have reported mid- and far-infrared emission. Jura (1986) discussed the frequency of detection for ellipticals and S0's in the *IRAS Point Source Catalog* (PSC) and Jura *et al.* (1987) presented the results of a more sensitive search through the *IRAS* data for additional ellipticals. Study of star formation in dwarf galaxies by Thronson, Bally, and Hacking (1987) produced additional *IRAS* data on small ellipticals and, especially, S0's. We primarily used these three sources in the following study. Additional galaxies were found as a result of a meandering search of the PSC. We make no claim for completeness here, but rather we wish to emphasize the wide range of infrared characteristics found for early-type galaxies and that star formation appears to be taking place in some. For the purposes of our work, we define a dwarf galaxy as one with a luminosity in the B passpand of less than 3×10^9 $L_\odot$, where $1\ L_\odot \equiv 3.8 \times 10^{33}$ ergs s^{-1} regardless of wavelength (not a universal convention).

Figure 1a shows the distribution of colors for the galaxies in our study. Galaxies have been plotted according to morphological type—either elliptical or S0—and blue luminosity. Because of uncertainties in morphological classification, only objects that appeared to be reliably classified as ellipticals were plotted as open circles in the figure. Only 28 objects are plotted, reflecting the difficulty in detecting the infrared emission from objects that are certainly not dust-rich (Rieke and Lebofsky 1986; Jura 1986).

A larger number of early-type galaxies were detected by *IRAS* than we show in our figure, but usually only at a single wavelength. Many early-type galaxies were detected at 60 and 100 μm, and we include a histogram of numbers versus $\log[F_{60}/F_{100}]$ in the right-hand side of Figure 1a. A region characteristic of the colors of "cirrus," following the summary of Helou, is enclosed by the dashed line.

The region in the two-color diagram that is occupied by galaxies (Fig. 1 of Helou 1986; our Fig. 1a) is nearly coextensive with the region occupied by Milky Way star-forming regions. In particular, the location in the diagram appropriate to emission from "infrared cirrus" also includes active star-forming regions. To illustrate this point, we adapt Figure 1b from Thronson and Mozurkewich (1987) which shows the location of total infrared emission from 29 well-studied star-forming regions in the Milky Way. The flux densities plotted in this figure are integrated over the surface area of molecular clouds. For details of these results, the reader is referred to Thronson and Mozurkewich. Star-forming regions appear systematically to the left of the locus of galaxy points (Helou's Fig. 1; our Fig. 1a), which we believe is due to the lack of a contribution from small grains in most of the clouds. A remarkable aspect of Figure 1b is that a number of sites of recent, massive star formation are close in color to the "cirrus" emission, despite being an environment with a radiation field that must be many times more intense than the general interstellar field. Inspection of the *IRAS* images of these regions shows clear enhancement over the background and/or foreground "cirrus" emission, so that these star-forming regions can be clearly identified. However, at the great distances of most galaxies, individual star-forming regions cannot, of course, be spatially resolved at far-infrared wavelengths, and their contribution to the composite light from galaxies can be indistinguishable from that of the inert "cirrus."

III. DISCUSSION

Early-type galaxies show a very wide distribution in our Figure 1a, as wide as that shown by Helou's large sample of primarily disk galaxies. There appears to be no particular concentration of early-type galaxies in any location in the diagram nor, in the limited sample that we presently possess, do giants and dwarfs appear segregated. The histogram, which might be more representative of early-type galaxies, indicates that there is a significant concentration of objects in the lower portion of the figure, roughly appropriate to the colors of "infrared cirrus." However, perhaps as many as one-third of the early-type galaxies have 60–100 μm colors very different from "cirrus."

Helou explained the distribution of his sample of galaxies in the two-color plot as the consequence of variations in the relative contribution from "cirrus" emission and dust associated with star-forming regions, plus the effects of radiation fields of varying intensity. Galaxies that are not creating stars at present, but with dust mixed with the diffuse ISM, are expected to appear near the dashed region in our figure. As the relative contribution from dusty star-forming regions increases, an object is found more to the upper left of the figure. The diagonal line in the figure is the locus of colors for a model of Désert (1986) for dust in a solar neighborhood radiation field (*lower right*) to one that is many hundred times more intense (*upper left*). Helou found that combinations of "cirrus" and star-forming emission would result in a distribution of points lying beneath the line for the Désert results. This is what we find for early-type galaxies. Since objects are found in the upper left of the Figure 1a, some ellipticals and S0's are apparently far from inert.

This conclusion may be quantified somewhat. Helou estimated the colors of galaxies within which the star-forming material and the "cirrus" contributed equally to the total infrared flux. A wide range of 12–25 μm colors were possible, since star-forming regions may not contribute much at short wavelengths (e.g., Cox and Mezger 1987; Persson and Helou 1987). However, the 60–100 μm ratio is sensitive to the two components that interest us, which was the motivation for making the effort to compile the data for the histogram. In particular, following Helou, if $\log[F_{60}/F_{100}] > -0.35$, roughly, more than half of the infrared flux is contributed by

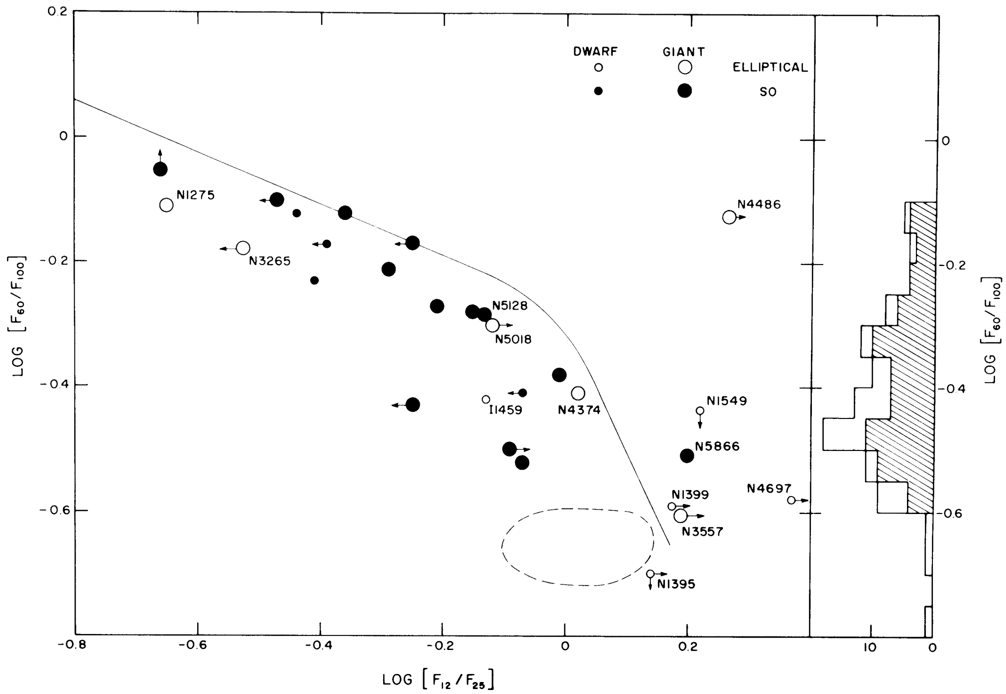

FIG. 1*a*

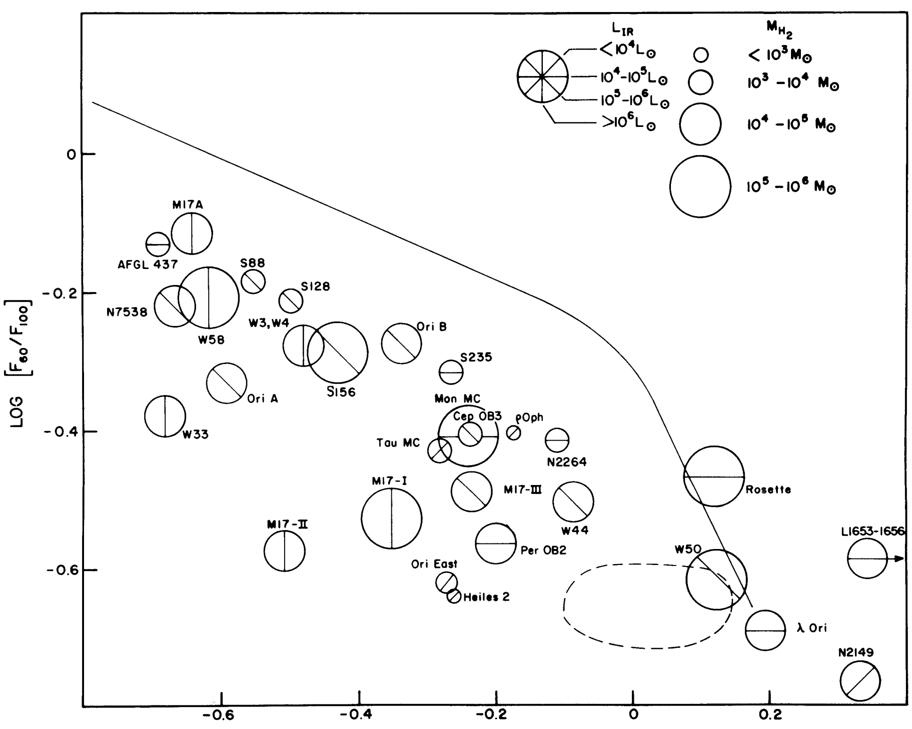

FIG. 1*b*

FIG. 1.—(*a*) A plot of *IRAS* colors for 28 elliptical and S0 galaxies. Colors of "infrared cirrus" emission are indicated by the dashed region and a model from Désert (1986) of dust emission is shown by the diagonal line. Detected elliptical galaxies are listed in Table 1. The histogram shows the number of early-type galaxies detected as a function of 60–100 μm color. Elliptical galaxies are the open boxes, and S0 galaxies are the hatched ones. The bin size is 0.05 in $\log[F_{60}/F_{100}]$. (*b*) A plot of *IRAS* colors for 29 large star-forming molecular clouds in the Milky Way, adapted from Thronson and Mozurkewich (1987). The size of the circles are proportional to the H_2 mass of the object, and the angle of the bar in the circle indicates the infrared luminosity.

TABLE 1

ELLIPTICAL GALAXIES

Name	Other ID	Type[a]	Distance (Mpc)	F_{12} (Jy)	F_{25} (Jy)	F_{60} (Jy)	F_{100} (Jy)	L_{IR} ($10^9 L_\odot$)	L_{IR}/L_B [b]	Remarks[c]
NGC 1275.......	3C 84	pec; Ep	52.5	0.86	3.82	5.76	7.50	37.	5.4	radio, X-ray galaxy
NGC 1395.......	...	E2; E2	15.7	0.12	< 0.087	< 0.078	0.29	0.05:	0.03:	shell galaxy
NGC 1399.......	PKS 0336−35	E1p; E1	12.9	0.09	< 0.06	< 0.087	0.34	0.03:	0.017:	
NGC 1549.......	...	E0–1; E2	9.3	0.10	0.06	< 0.066	0.18	0.0093:	0.01:	shell galaxy
NGC 3265.......	...	E4; ...	19.3	< 0.25	0.86	2.18	3.26	2.0	11	
NGC 3557.......	PKS 1103+002	E3; E3	32.1	0.13	< 0.084	0.19	0.75	0.77	0.13	
NGC 4374.......	M84	E1; E1	13.5	0.20	0.19	0.50	1.28	0.28	0.09	radio, X-ray galaxy
NGC 4486.......	M87, Vir A	E^+0–1; E0	13.5	0.29	< 0.15	0.33	0.44	0.14	0.026	cD, radio galaxy
NGC 4697.......	...	E6; E6	11.7	0.29	< 0.12	0.33	1.24	0.17	0.066	
NGC 5018.......	...	E3?; E4	31.4	0.16	< 0.21	1.02	2.03	2.6	0.63	shell galaxy
IC 1459	...	$E3^+$; E4	14.8	0.17	0.23	0.45	1.18	0.31	0.16	

NOTE.—The majority of the infrared data are from Jura 1986 and Jura *et al.* 1987.

[a] Morphological classification from *Second Reference Catalog of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1977) given first, followed by classification from *A Revised Shapley-Ames Catalog of Bright Galaxies* (Sandage and Tammann 1981).

[b] The blue luminosity (L_B) is defined as the flux through the standard B passband, 1 $L_\odot = 3.8 \times 10^{33}$ ergs s^{-1}.

[c] "Shell galaxy" refers to membership in the southern hemisphere survey of such objects by Malin and Carter 1983.

star-forming regions. About one-third of the objects in our sample satisfy this simple criterion, and their infrared emission may be dominated by emission from star-forming regions. As already discussed, there is an ambiguity in discussing the nature of infrared emission from objects in the lower right of the figure as both inert "cirrus" emission, and some sites of star formation show emission that places them in this location.

a) *Elliptical Galaxies and Star Formation*

Although conventional wisdom holds that star formation has ceased in early-type galaxies, Figure 1*a* shows that this may not be the case. One intriguing result is for the elliptical galaxies, which, even though our sample size is small, deserve special comment. Table 1 lists the parameters for the 11 elliptical galaxies that have sufficient data to be plotted in our figure. The number of ellipticals in Figure 1*a* is less than the number actually detected by *IRAS* because (1) the figure includes only galaxies that seemed to be unambiguously ellipticals and (2) detection in at least three *IRAS* bands was usually necessary to place a point into the plot. Our histogram shows that three times the number of elliptical galaxies that appear in the plot were detected in at least two *IRAS* bands. About half the ellipticals appear clustered close to the region corresponding to "cirrus" emission for which the infrared flux may be dominated by dust mixed with the general ISM. It is certainly possible that star formation is taking place in these objects, since many well-studied Milky Way star-forming regions have infrared colors comparable to the ellipticals.

Four elliptical galaxies lie far enough away from the "cirrus" emission region that we consider them to be unambiguously active galaxies: NGC 5018, NGC 3265, and the well-known peculiar ellipticals, NGC 1275 and NGC 4486 (M87). Collisions, central explosions, extreme rates of mass infall, and other unusual processes have been suggested for the variety of emission found for the latter two objects. Dust mixed with the gas in the core of these systems may absorb and reradiate emission from these processes, resulting in a strong infrared flux. It is, of course, entirely possible that the same processes are taking place at somewhat lower levels in otherwise normal elliptical galaxies. For the purposes of this *Letter*, we assume that, unless otherwise noted, star formation dominates the emission from objects in the upper left of the two-color diagram. In our study, that leaves NGC 5018 and NGC 3265 as apparently bona fide, active star-forming normal elliptical galaxies. Photographs and a discussion of the former object as an example of a dusty elliptical appear in Schweizer (1986). The latter object has a large 25–60 μm ratio, which is often a characteristic of a Seyfert nucleus (de Grijp *et al.* 1985).

It is interesting to estimate the rates of star formation, $\dot{M}$, in the objects studied here. Thronson and Telesco (1986) recently proposed a technique to calculate $\dot{M}$ from infrared observations (similar techniques have been applied at other wavelengths by Kennicutt 1983 and Gallagher, Hunter, and Tutukov 1984). Thronson and Telesco found that the current star formation rate (SFR), as measured by the infrared emission, may be expressed as $\dot{M}_{IR}$ ($M_\odot$ yr^{-1}) = 6.5×10^{-10} L_{IR} ($L_\odot$) for a Salpeter initial mass function (IMF) that extends from 0.1 to 100 $M_\odot$. The coefficient increases significantly if the upper mass limit to the IMF decreases, which leads to a significant uncertainty in $\dot{M}$. For example, if the upper limit is only 60 $M_\odot$, then the coefficient is doubled. From the table, we find that the four elliptical galaxies that appear to be actively forming stars have SFRs in the range 0.3–25 $M_\odot$ yr^{-1}. The two normal ellipticals—NGC 5018 and 3265—have rates in the range 0.5–1 $M_\odot$ yr^{-1}, in comparison to the star-formation rate in the Milky Way, often estimated to be about 5 $M_\odot$ yr^{-1}. The rates that we calculate for the elliptical galaxies are about two orders of magnitude lower than those estimated by Jura (1986), who assumed that gravitational collapse of clouds powers the infrared emission from early-type galaxies.

What is the source of the gas for star formation? Some material may be left over from the epoch of galaxy formation, but mass returned to the ISM from evolved stars or gas accumulated via a recent merger can plausibly sustain the observed rates of stellar creation. Faber and Gallagher (1976) estimated that the mass-return rate for elliptical galaxies is $\sim 1\text{–}2 \times 10^{-11}\ L_{\rm bol}\ M_\odot\ {\rm yr}^{-1}$. We assume that mass loss from evolved stars balances stellar mass formation and use the star formation rate as a function of infrared luminosity (above) to find the criterion for this: $L_{\rm IR}/L_{\rm bol} \approx 0.015\text{–}0.03$. If $L_{\rm bol} \approx 20L_B$, then for star formation sustained by mass loss, $L_{\rm IR}/L_B \approx 0.3\text{–}0.6$. Table 1 includes luminosity ratios for the elliptical galaxies in our sample. Considering the considerable uncertainty in this series of calculations, old stars in some of the objects may be returning enough material to sustain the creation of new stars. Furthermore, we note that since the luminosity ratios for most objects in the table are very much smaller than the criterion that we just produced, we suggest that mass-return might *easily* be supporting the observed rate of star formation. If $L_{\rm IR}/L_B$ approaches or exceeds unity in a galaxy, some other reservoir of gas should be considered to sustain stellar creation. It is possible that ellipticals do not have the large "ballast" of a gas-rich ISM from which star formation can draw. Thus, the rate of formation of new generations of stars becomes sensitively tied to the numbers and the mass function of previous generations of stars.

One prediction for mass-loss–fueled star formation is that the kinematics of gas in a galaxy should be similar to that of the stars. However, observations of some ellipticals show a velocity and momentum structure in the gas that is inconsistent with mass loss from evolved stars (e.g., Wilkinson *et al.* 1986). The orbital velocity of the gas exceeds that of the stellar population by a factor of 2 or 3. In addition, the velocity dispersion of stars in an elliptical galaxy is quite large, a few hundred km s^{-1}. Mass lost by giant stars could be expected to have similar velocities relative to the ambient ISM. Thus, material from evolved stars, colliding with an ambient ISM, would have temperatures equivalent to $T \approx mv^2/3k \approx 4 \times 10^5\ v_{100}^2$ K. In the very diffuse ISM in early-type galaxies, cooling times are expected to be long, and high-temperature gas is not conducive to active star formation.

Shell-like structure, as well as the velocity of the gas, might be explained as the consequence of galaxian merger (e.g., Quinn 1984; Hernquist and Quinn 1987), which should be considered as a possible source of star-forming gas. For example, six of the infrared-emitting ellipticals in Table 1 are in the region of the sky surveyed for shells by Malin and Carter (1983). Of these six, three objects were found to have shells, indicative of low-velocity mergers. Many infrared-bright galaxies show evidence of having suffered close encounters. We, thus, suggest that many dusty, star-forming elliptical galaxies are in the last stages of galaxian merger. Phase-space mixing of stellar orbits during mergers may produce systems with kinetic properties indistinguishable from ellipticals (e.g., Toomre and Toomre 1972). Subsequent consumption or expulsion of the ISM may then produce an object that is morphologically similar to ellipticals. Furthermore, most elliptical galaxies are found in clusters or groups, but rarely alone, and might be expected to be the product of a higher frequency of encounters.

Thronson and Telesco estimated that for $L_{\rm IR}/L_B > 10$, the present-day star-formation rate exceeds that averaged over the past 10^9 yr, although their analysis has limited application to the types of galaxies considered here. One normal elliptical in Table 1 stands out again: NGC 3265. It is a low visual luminosity object, apparently a dwarf, and its H I mass distribution and kinematics have been recently studied by Lake, Schommer, and van Gorkom (1987). Its infrared luminosity is moderately large and $L_{\rm IR}/L_B$ is the highest in our small sample. Using a term that has the triple advantage of being succinct, ill-defined, and having an erotic fascination for scientific organizing committees, we suggest that NGC 3265 is a candidate for classification as a *starburst* dwarf elliptical galaxy. However, as noted above, the object is also a candidate for having a Seyfert nucleus.

b) Some Comments on the IRAS Two-Color Diagram

On the basis of this investigation into the colors of early-type galaxies, as well as our ongoing study of irregulars, we propose alternative explanations for the observed distribution of galaxies in the infrared color-color diagram. In some respects, our interpretation is in disagreement with earlier work.

In the first place, we believe that luminosity has little or nothing to do with the position of a galaxy in a plot such as our Figure 1*a*. As Figure 1*a* shows, a respectable number of "sedate" early-type galaxies are found scattered over a wide range of the figure, with some in the upper left. More significantly, the most abundant class of star-forming galaxy, the irregulars, heavily populate the upper left of the figure (see the data in Thronson and Telesco 1986), despite infrared luminosities that are orders of magnitude less than the luminous giant galaxies that dominate many infrared two-color plots. Soifer, Houck, and Neugebauer (1987) state that the upper left of a color-color diagram, such as our Figure 1*a*, is occupied by galaxies undergoing "starbursts," although Gallagher, Hunter, and Tutukov (1984) (see also Thronson and Telesco) found that irregular galaxies are typically forming stars at relatively constant rates. It is possible that the belief that $\log[F_{60}/F_{100}]$ is positively correlated with infrared luminosity arises from studies of bright galaxies in flux-limited samples, such as the recent work by Soifer *et al.* (1987; see their Fig. 6*a*). Flux-limited surveys strongly select in favor of high-luminosity galaxies and against the abundant irregulars, which could lead to the conclusion that low-luminosity galaxies are not found in some parts of a color-color diagram. Helou (1987) identified what we also believe to be an important galaxian characteristic in determining the location of objects in infrared color-color plots: the "activity," the amount of star formation *per area* of the galaxy. Thus, the small Magellanic irregulars and the most luminous "starburst" galaxy will occupy similar regions of the plot.

Apparently, galaxies in the upper left of the infrared color-color diagram have larger values of the ratio $L_{\rm IR}/L_B$ than do those in the lower right, as Helou points out, although interpretation of the significance of this effect must be undertaken carefully. Helou assumes that L_B is a measure of the number of young stars in galaxies that are forming stars at a high rate. Thus, L_{IR}/L_B should be directly related to the amount of extinguishing dust that surrounds young stars. In contrast, Gallagher, Hunter, and Tutukov (1984) and Thronson and Telesco (1986), among others, in their studies of small galaxies, have shown that very modest star formation rates maintained for long periods of time are sufficient to produce enough older, intermediate-mass stars, with a combined blue luminosity that will overwhelm the light from very young stars. Agreeing with this line of reasoning, we believe that variations in L_{IR}/L_B among many galaxies can be largely a consequence of variations in the global star-formation rate averaged over two different time scales.

IV. SUMMARY

We find that the infrared colors of about one-third of our modest sample of early-type galaxies are consistent with ongoing star formation, although we acknowledge that a contribution to the infrared emission from an "active" nucleus might play an important role in some objects. Apparently star formation has not ceased in some elliptical and S0 galaxies and may be fueled by mass loss from evolved stars or out of the rubble of galaxian mergers. Of four plausible candidate star-forming ellipticals, three show evidence for accretion and/or merger. Rates of star formation are in the range 0.1–1 $M_\odot$ yr^{-1} for the normal galaxies that appear to be forming stars, but there is significant uncertainty in estimating this quantity. A majority of early-type galaxies that were detected by *IRAS* have 60–100 μm colors consistent with emission predominantly from "cirrus," but we emphasize that this statement does *not* mean that star formation has ceased in these objects. Several well-known star formation regions in the Milky Way have infrared colors comparable to that of "cirrus."

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