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DO DENSITY WAVES TRIGGER STAR FORMATION?

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ABSTRACT

A comparison of $B-V$ colors, blue and far-infrared surface brightnesses, metallicities, and star formation rates calculated from Hα and UV fluxes reveals no difference in the average star formation rates for galaxies with and without grand design spiral structure. This implies that strong density waves do not trigger a significant excess of star formation compared to that in similar galaxies without a wave. Density waves organize the gas and young stars into spiral arms because of the flow pattern, and they may influence the formation and destruction of the largest cloud complexes, but they appear to contribute less than 50% to the overall star formation rate. Substantial triggering of star formation by density waves may be limited to peculiar cases with very strong shocks, such as interacting galaxies and some barred galaxies.

Subject headings: galaxies: photometry — galaxies: structure — stars: formation

I. INTRODUCTION

The spiral structure in most grand design galaxies results from density waves or wave modes (Lin and Shu 1964). The wave pattern was originally thought to be weak, with visible spiral arms resulting from triggered star formation (Roberts 1969). But recent red and near-infrared observations (Schweizer 1976; Strom, Jensen, and Strom 1976; Elmegreen and Elmegreen 1984, hereafter EE84; Kennicutt and Edgar 1986) reveal large arm amplitudes, which imply that the visible arms are essentially the waves themselves, with negligible amplification by triggered star formation. The triggering hypothesis should therefore be examined more critically.

The profusion of young stars and H II regions in galactic spiral arms does not imply that density waves trigger star formation. The gas flows more slowly through an arm than between the arms (Roberts 1969), so most of the star formation in a galaxy will appear in the arms even if star formation merely follows the gas, without any substantial trigger. The slight blue colors of the arms also require no star formation trigger; they could result instead from the differential compression of stars and gas with different velocity dispersions (the gas and blue stars, having a small velocity dispersion and scale height, should be compressed more than the red stars, which have a large velocity dispersion and scale height).

Density waves may only trigger the growth or conglomeration of large cloud complexes from smaller clouds, without generally affecting the average rate of star formation per unit gas mass in these clouds. The H II regions and molecular clouds in spiral arms are much larger than they are between the arms (Mezger 1970; Georgelin and Georgelin 1976; Stark 1979; Kennicutt and Hodge 1980; Rumstay and Kaufman 1983; Cohen *et al.* 1985; Dame *et al.* 1986; Stark *et al.* 1986), but this size variation does not imply that an excess of star formation has been triggered by the arms. Azimuthal variations in the star formation rate per unit gas mass have not yet been measured, and they may be very difficult to measure because of unknown variations in the opacity of H I, the CO to H_2 conversion factor, and the initial stellar mass function.

The purpose of this paper is to compare star formation rates in galaxies with and without grand design spiral structure (§ II, III and IV). A recent catalog of spiral arm classes for 745 galaxies is used (Elmegreen and Elmegreen 1987; hereafter EE87). The arm classifications were made from glass copies of the Palomar Observatory Sky Survey and from Atlas photographs. Galaxies with arm classes 1–4 are "flocculent," and contain no strong density waves, while galaxies with arm classes 5–12 are "grand design," and probably contain such waves (EE84). The variation in arm class correlates approximately with the regularity of the spiral structure. Arm class 1 galaxies, for example, are very irregular, and usually of the Magellanic type (Sm). Arm class 2 galaxies, like NGC 7793, have large bright patches distributed irregularly around the disks, sometimes in short spiral-like pieces. Arm class 3 galaxies, like NGC 2841, have numerous *strings* of bright patches, distributed around the disks in an irregular spiral pattern. Arm class 5 galaxies are like M33, with patchy but generally symmetric two-arm spiral structure. Arm class 9 galaxies are like M101, with several long and continuous spiral arms. Arm class 12 galaxies are like M100 or M51, with two prominent and symmetric arms.

Similar comparisons between spiral arm type and star formation rate have been discussed elsewhere. Romanishin (1985) found that the grand design galaxies in our previous catalog of 305 arm classes (Elmegreen and Elmegreen 1982; hereafter EE82) are slightly bluer than flocculent galaxies, and Phillipps and Disney (1985) found that the grand design galaxies in the same sample have slightly lower surface brightnesses. McCall and Schmidt (1986) classified all galaxies with recognized supernovae and found that the supernova rate is approximately the same in grand design and flocculent types. The larger sample of galaxies in the present paper confirms the first two of these correlations, but the statistical uncertainties are too large to make the correlation significant. The implication of the third, that the massive star formation rate per unit area in a galaxy is independent of arm class, is also found here, but again the uncertainties are large.

The first attempt to compare the star formation rates for galaxies with different spiral structures was made by Roberts, Roberts, and Shu (1975). They suggested that the luminosity class of a galaxy (van den Bergh 1960) depends on the spiral arm shock strength because strong shocks produce thin and bright spiral arms. They noted that the most luminous galaxies have the fastest rotation speeds. Because the shock strength depends on the rotation speed, the fast-rotating galaxies were thought to be the most luminous because their strong shocks triggered the most star formation. In fact, the correlation between luminosity class and luminosity is essentially the result of a correlation between luminosity class and galaxy size (Iye and Kodaria 1976), with the star formation rate per unit area independent of the luminosity class, as discussed in § V. The other conclusions by Roberts, Roberts, and Shu (1975) may still be true, i.e., that the quality of the spiral arm system in a galaxy depends on the mass distribution and rotation speed, but these conclusions apparently say more about density waves than about star formation.

Proof of the density wave triggering hypothesis may be very difficult, considering the potential problems with calibrations of gas mass and star formation rate. A correlation between the local star formation rate in a galaxy and the presence of a wave mode might also arise even if density waves do not commonly trigger star formation. This is because the strength of a particular mode can depend on gas content. The gas may damp the highest order wave modes and leave only the symmetric mode (Kalnajs 1972; Roberts and Shu 1972; Shu 1985). The gas and stars that form in the gas may also contribute to the self-gravity of the wave, because, even though the average gas and young-star density is less than the average old-star density in the galactic midplane, the velocity dispersion of the gas and young stars is low. Such gravitational contributions can make a wave stronger than it would be with little gas (Sellwood and Carlberg 1984). Thus spiral arm quality, as measured by the arm class or luminosity class (and determined partially by the strength of a density wave) could correlate with galaxy surface brightness or color (as determined by the star formation rate) because both the spiral wave amplitude and the star formation rate depend on the gas density (but not necessarily on each other).

Even though no correlations between star formation rates and spiral arm class are found here, density waves may still trigger star formation in some situations. The constraints on such triggering, and other implications from the present study, are discussed in § VI.

II. STAR FORMATION RATES, COLORS, AND SURFACE BRIGHTNESSES FOR GALAXIES WITH DIFFERENT ARM CLASSES AND HUBBLE TYPES

Figure 1 shows the distribution with spiral arm class of various quantities that measure the average star formation rate per unit area in a galactic disk. The Hα star formation rate from Kennicutt (1983) was divided by the galaxy area, which was determined from the angular size D_0 and the distance from V_0 in the RC2 of de Vaucouleurs, de Vaucouleurs, and Corwin (1976). (A Hubble constant of 50 km s^{-1} Mpc^{-1} was used for this plot to be consistent with Kennicutt.) The UV star formation rate per unit area and the UV rate divided by the total galaxy mass are from Donas and Deharveng (1984), using their distances and angular diameters D_{25} from the RC2. The $B-V$ color corrected for internal extinction, $B-V_{\rm corr}$, is the same as $(B-V)_T{}^0$ in the RC2, and the average surface brightness within the ellipse at 25th magnitude per square arc second, $m_{25,\,\rm corr}$, is m'_{25} in the RC2. The far-infrared luminosity per unit area is from log (FIR) in the *IRAS* galaxy catalog (Lonsdale *et al.* 1985) divided by the angular area from D_0 in the RC2. Different symbols are for different Hubble types: squares are for early types (Sa, Sab, Sb), circles are for intermediate types (Sbc, Sc, Scd), and diamonds are for late types (Sd, Sdm, Sm). Symbols with dots are for barred types SAB or SB.

No systematic correlations between any of these star formation properties and the presence of a prominent wave mode are evident. Arm class 1 galaxies have high star formation rates per unit area, as expected for these Magellanic-type irregular galaxies. Arm class 2 galaxies have high star formation rates (and bluer colors, etc.) than arm class 3 galaxies, presumably because the bright patches in AC2 galaxies are from star formation, and these patches are more intense than the patches in AC3 galaxies. (Some of the patches in AC3 galaxies could be weak density waves or density ripples; EE84). Aside from these variations, the star formation rate does not appear to depend on the arm class. For intermediate Hubble types without bars (SAbc, SAc, and SAcd), which might be expected to show the greatest variations in star formation rates (Romanishin 1985), the $B-V$ colors vary from 0.54 ± 0.13 to 0.51 ± 0.07 to 0.51 ± 0.10 magnitudes for flocculent (arm classes 1–4) to intermediate (arm classes 5–9) to grand design (arm class 12) spiral types. Similarly, the UV star formation rate per unit area in Donas and Deharveng (1984) varies from 0.0054 ± 0.0038 to 0.0044 ± 0.0025 to 0.0045 ± 0.0007 $M_\odot$ kpc^{-2} yr^{-1} for the three groups of arm classes; the star formation rates per unit area in Kennicutt (1983) vary from 0.0064 ± 0.0025 to 0.0074 ± 0.0071 to 0.0089 ± 0.0089 $M_\odot$ kpc^{-2} yr^{-1}, and the average blue surface brightnesses in RC2 vary from 13.7 ± 0.55 to 14.0 ± 0.40 to 14.2 ± 0.51 mag arcmin^{-2}. These variations are so small that the average star formation rate cannot depend strongly on the presence of a density wave.

This conclusion assumes that each measure of star formation has been corrected adequately for the galaxy's internal absorption. These corrections are only approximate. The absorption could possibly vary from galaxy to galaxy in such a way that the light from wave-triggered star formation is absorbed much more than the light from wave-independent star formation. Then the excess Hα, UV, or blue light from such triggering may go unnoticed. The excess should still be visible in the infrared, however, but possibly not by *IRAS* if a substantial amount of the radiation from star-forming regions has too long a wavelength to be observed by *IRAS*.

Figure 2 compares the star formation properties of galaxies with different Hubble types to emphasize that the well-known correlations between star formation rate and Hubble type are easily recognized from the data. Different symbols are for different spiral arm classes: squares are for flocculent galaxies (AC 1–4), circles are for intermediate arm classes (AC 5–9) and diamonds are for grand design galaxies (AC12). Symbols with dots have bar types SAB or SB.

Figure 3 shows how the arm classes for galaxies in Figures 1 and 2 are distributed with Hubble type. The arm classes and Hubble types are dispersed by several tenths in the figure to avoid overlaps. Galaxies with arm classes 10 and 11 in EE82 (barred and binary galaxies, respectively) were given different arm classes in EE87, based only on the arm structure itself. Thus there are no AC10 or AC11 galaxies in the present survey.

III. A COMPARISON OF METALLICITIES FOR GALAXIES WITH DIFFERENT ARM CLASSES

The metallicities of H II regions in galaxies studied by McCall (1982) are plotted versus the arm classes and Hubble

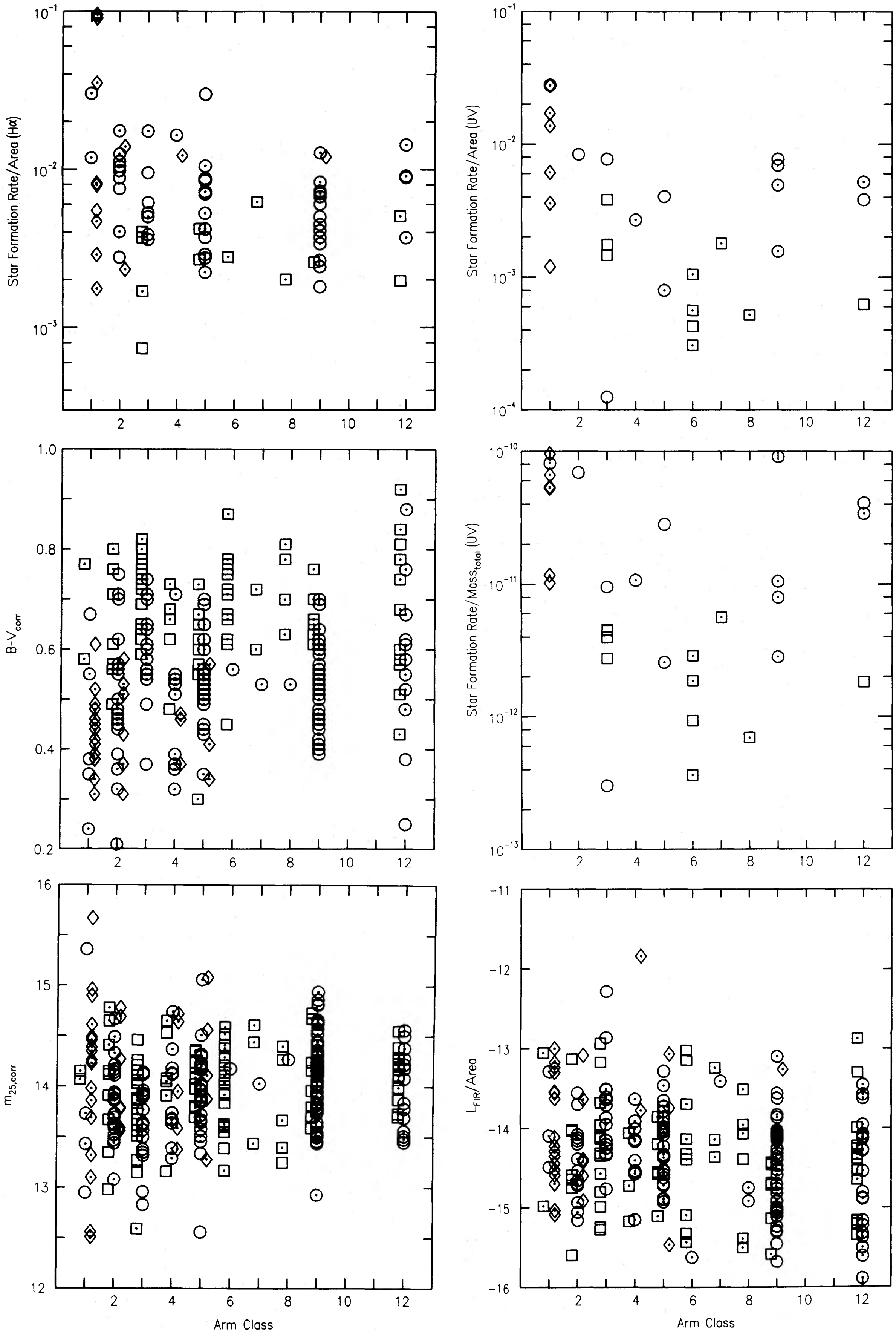


FIG. 1.—Various measures of the star formation rate per unit area in galaxies are plotted vs. the spiral arm classes. Star formation rates per unit area are in $M_\odot$ kpc^{-2} y^{-1}; the $B-V$ colors are in magnitudes, the surface brightnesses are in magnitudes arcmin^{-2}, and the far-infrared luminosities per unit area are in W m^{-2} arcmin^{-2}. Symbols denote Hubble type: *squares*, early types (Sa, Sab, Sb); *circles*, intermediate types (Sbc, Sc, Scd); *diamonds*, late types (Sd, Sdm, Sm). Symbols with dots are barred Hubble types, SAB or SB. No correlations are evident.

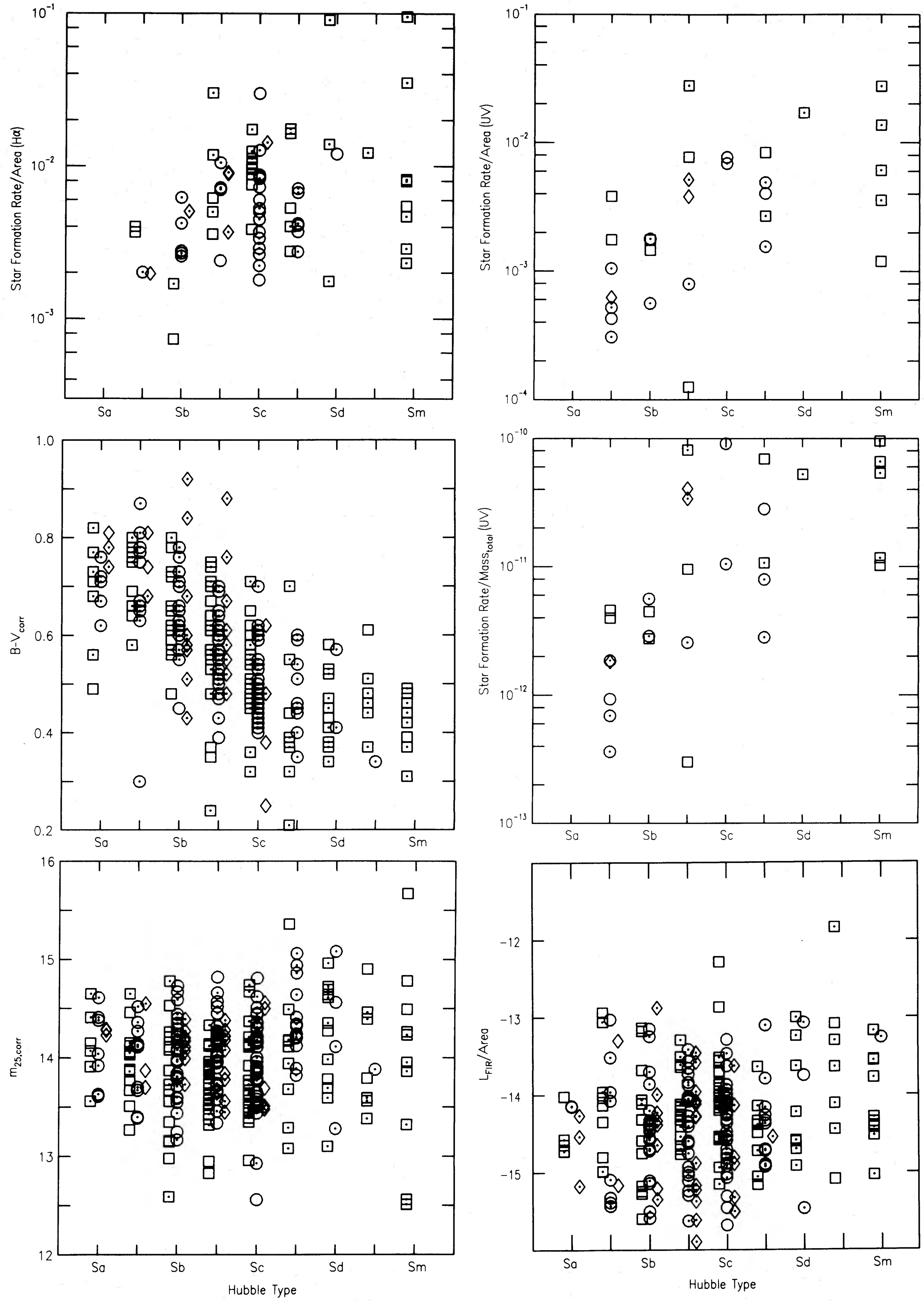


FIG. 2.—Star formation rates from Fig. 1 plotted against Hubble type. Symbols denote arm class: *squares*, flocculent (AC 1–4); *circles*, intermediate (AC 5–9); *diamonds*, grand design (AC 12). Symbols with dots are barred, SAB or SB. Expected correlations between Hubble type and the galactic color or star formation rate are apparent.

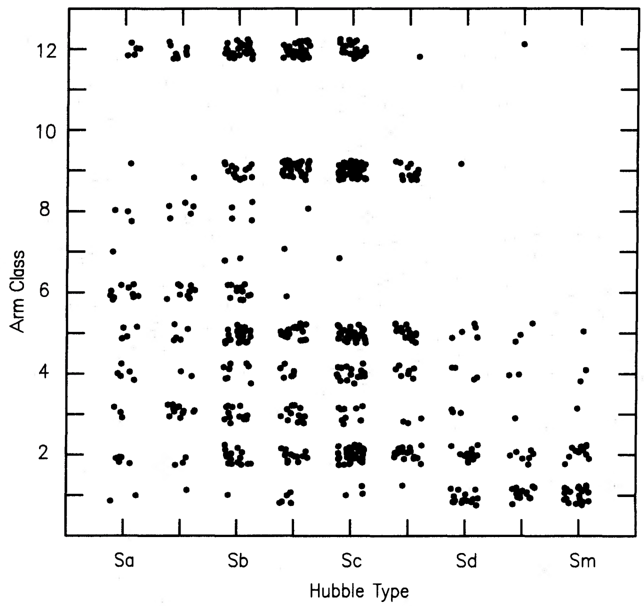


FIG. 3.—Distribution of spiral arm class with Hubble type is shown for the galaxies included in Figs. 1 and 2. Individual values of the arm classes and Hubble types are given random dispersions in order to avoid overlaps. Original arm classes 10 and 11 (EE82) are not considered in the present classification system (EE87). There is no systematic correlation between arm class and Hubble type.

types in Figure 4. Each H II region is a separate symbol. The well-known correlation with Hubble type is evident (late types have larger oxygen emission-line intensities and lower metallicities). Unfortunately, this correlation with Hubble type is also present to some extent on the plot versus arm class, because of a slight correlation between the Hubble type and arm class in this sample. Thus, the high points in arm class 1 could be high only because that galaxy has a late Hubble type (Sm). Aside from this, the metallicity data does not suggest that a correlation with arm class exists.

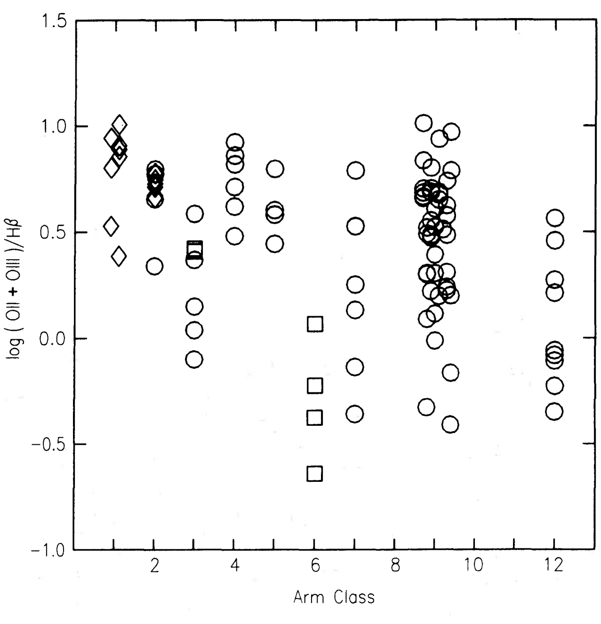
IV. A COMPARISON OF STAR FORMATION PROPERTIES FOR GALAXIES IN DIFFERENT GROUP ENVIRONMENTS

The presence of a density wave mode in a galaxy correlates with group environment, in the sense that grand design galaxies tend to be located only in dense groups, while flocculent galaxies occur in groups of all densities (Elmegreen and Elmegreen 1983; EE87). The relevant correlation from EE87 is reproduced here, in Figure 5*a*. One interpretation of the results of the previous sections is that density waves trigger star formation, but that such waves are transient in galaxies. In that case, if all galaxies have waves for the same fraction of the time, then the average star formation properties will be the same whether or not a wave mode is currently present. This interpretation can be evaluated by comparing the star formation properties of galaxies in groups with various densities. If the waves are transient, then galaxies in dense groups must have waves for a larger fraction of the time than galaxies in low-density groups. If these waves trigger star formation, then the star formation rates in dense groups should be larger than the star formation rates in low-density groups.

Figure 5 shows the colors (from RC2), star formation rates per unit area (from Kennicutt 1983, D_0 and V_0 as above), and average surface brightnesses (from RC2) versus the group crossing rates for all galaxies in the Geller and Huchra (1983) group catalog that could be given arm classes (as in EE87). No correlations between group crossing rate (i.e., group density) and these measures of star formation rate are evident. This is consistent with Brinks and de Jong (1985), who find that the infrared (*IRAS*) star formation rates are essentially the same for field, group, and Virgo-cluster galaxies.

V. THE LUMINOSITY CLASS AS A MEASURE OF GALAXY SIZE

The van den Bergh (1960) luminosity classification system is a qualitative measure of the brightness or prominence of spiral arms in blue images of galaxies. It is similar in some respects to the arm classification system (see comparison in EE82),



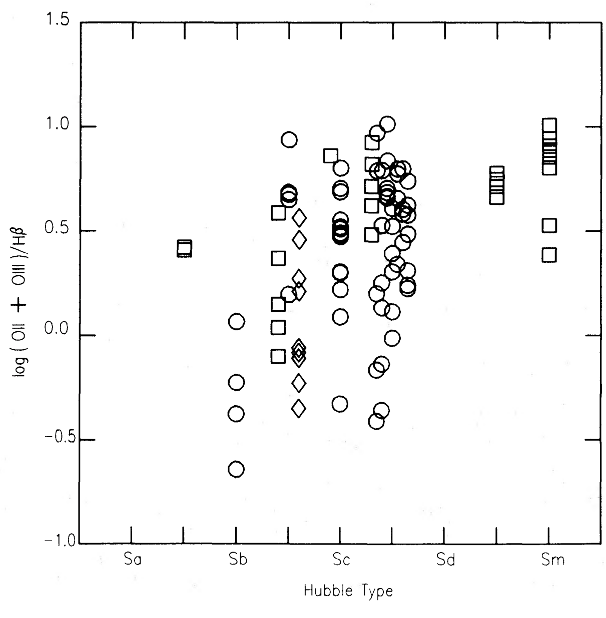


FIG. 4.—Ratio of the oxygen to hydrogen emission-line strengths from McCall (1982) are plotted vs. arm class and Hubble type. As in Figs. 1 and 2, the symbols denote Hubble types for the plot vs. arm class, and they denote arm class for the plot vs. Hubble type.

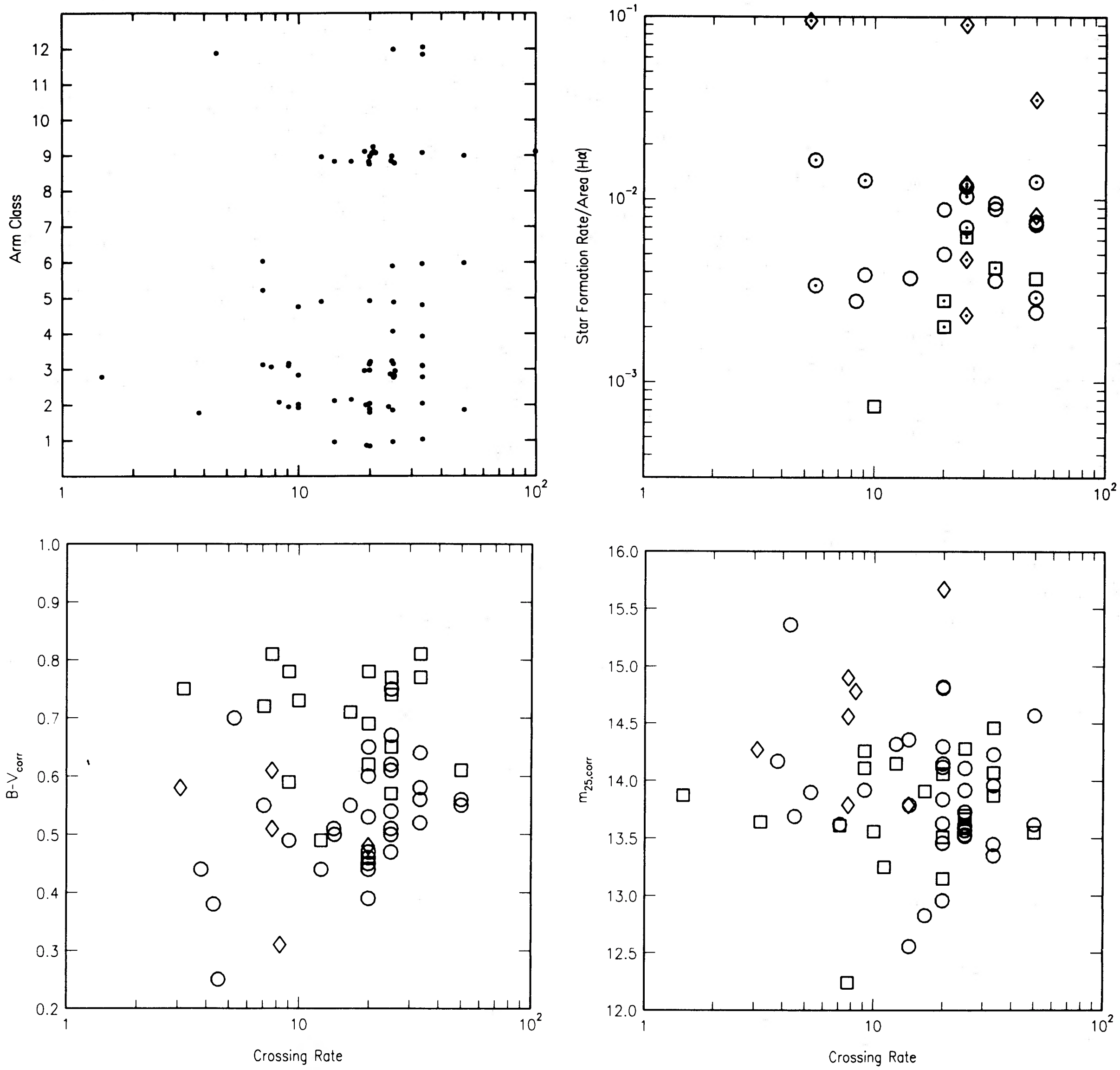


FIG. 5.—Arm classes for galaxies in groups are shown as a function of the group crossing rate (measured in units of the Hubble constant, from Geller and Huchra 1983). Intermediate and grand design galaxy types occur preferentially in dense groups (large crossing rates). Various measures of the star formation rate are also shown vs. the group crossing rate. Symbols represent Hubble and bar types, as in Fig. 2. No bar types are included in the plots of arm class, $m_{25,\,\mathrm{corr}}$ or $B-V_{\mathrm{corr}}$ vs. crossing rate because only the nonbarred galaxies have spiral structures that correlate with crossing rate. Bar types (symbols with dots) are included in the plot of star formation rates, however. No correlations between star formation properties and crossing rate are evident.

although the latter emphasizes the symmetry and continuity of the arms, regardless of their relative strengths or brightnesses. Luminosity class I galaxies have the strongest arms, followed by luminosity classes II–V.

The luminosity class gets its name from the fact that the prominence of spiral arms correlates with the total luminosity of a galaxy. This correlation is shown in Figure 6, where all galaxies with luminosity classes in the RC2 are plotted. The luminosity was determined from the product of the blue-band flux ($10^{-0.4B_T^0}$) and the square of the velocity (V_0), from the RC2. The radii (in kpc, from $D_0 V_0/[2H_0]$, using $H_0 = 100$ km s^{-1} Mpc^{-1}) and average surface brightnesses (from m'_{25}) are also plotted against the luminosity classes in Figure 6. Evidently, the surface brightnesses of galaxies are nearly constant (Freeman 1970), so the primary cause for the variation in luminosity with luminosity class is the galaxy size (Iye and Kodaria 1976). Figure 6 also demonstrates that the galaxy luminosity correlates very well with area (in kpc^2), which has been known for a long time (de Vaucouleurs 1957).

The constancy of the average surface brightness implies that the average star formation rate per unit area is constant for galaxies with different luminosity classes. If luminosity class correlates with density wave shock strength (Roberts, Roberts, and Shu 1975), then these shocks have little influence on the average star formation rates in galaxies.

VI. DISCUSSION

The figures suggest that the space- and time-averaged star formation rates in disk galaxies are independent of the presence of density wave modes. One interpretation is that density waves rarely trigger star formation, and that star formation is usually controlled by local processes, which operate independently of a wave (e.g., Seiden and Gerola 1982). These local processes must be present in irregular galaxies, for example, because star formation can be very active there, even without density waves (Hunter and Gallagher 1986). When the observational evidence usually used to support the density wave triggering hypothesis was recently examined (Elmegreen 1986), no unambiguous confirmation of this triggering could be found. Each piece of evidence either had an alternative interpretation, in which density waves do not trigger star formation, or the former evidence was found to be inconsistent with modern observations. Thus density waves may not commonly trigger star formation.

There are other interpretations of the figures. Density waves may trigger star formation in the arms and inhibit it in the interarm regions, leaving the overall star formation rate the same as in a similar galaxy without a wave. The increase in the star formation rate per unit gas mass in the arms cannot be very large, however, even if the star formation rate in the interarm region decreased to zero. For a typical arm/interarm brightness contrast of 4 (Schweizer 1976; EE84), the interarm region contains only one-fifth of the disk luminosity. If the star formation rate in the interarm region decreased from the average value per unit mass to zero because of some inhibition, then the star formation rate per unit mass in the arm would have to increase by 20% to maintain the same total star formation rate in the galaxy. Thus the contribution to star formation from spiral arm triggering is at most 20% if interarm inhibition is what maintains the constant rate suggested by the figures. Nevertheless, the azimuthal variation of the star formation rate

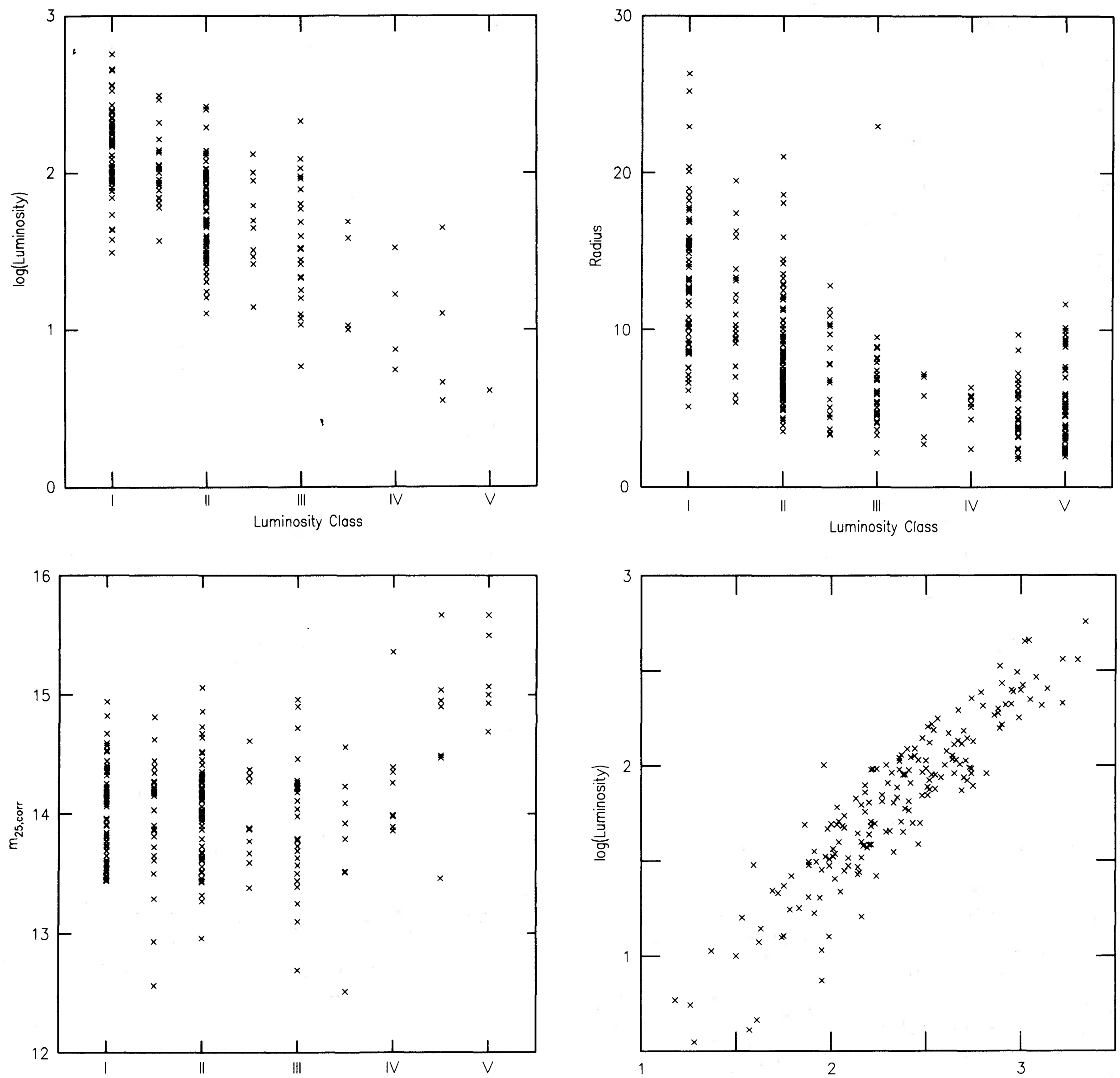


FIG. 6.—Luminosity and luminosity classes of galaxies are shown as functions of galaxy size (in kpc) and surface brightness (in mag arcmin^{-2}). (See § V for definitions of these quantities.) All galaxies in the RC2 which have luminosity classes are included. Luminosity of a galaxy appears to depend primarily on the galaxy size, all galaxies having similar surface brightnesses.

per unit gas mass should be measured, if possible. Phase-dependent variations in the calibrations for the total gas mass and star formation rate may make this measurement difficult.

The constancy of the star formation rate per unit area could also be consistent with density wave triggered star formation if the waves trigger star formation in the outer regions where the average density is otherwise too low to form stars. Then the general triggering throughout the disk may be accompanied by an enlargement in the visible disk area, with a fixed ratio of the total star formation rate to the total area. In fact, grand design galaxies are $\sim 50\%$ larger than flocculent galaxies (EE87), so either the wave is responsible for this larger size (by triggered star formation, for example), or the larger galaxies are more susceptible to wave formation (by a companion galaxy, for example). In either case, the observation of a constant star formation rate per unit *total* area implies that the star formation rate per unit *local* area (at some fixed radius in the disk, for example) is larger in grand design than in flocculent galaxies. This is because most galaxies have similar exponential-like intensity profiles, $I(R) = I_0 e^{-\alpha R/R_{25}}$, out to the radius $R_{25} = D_0/2$, with an approximately constant extrapolated central surface brightness, I_0 (Freeman 1970). The value of α is also approximately constant for most spiral galaxies, because $I(R_{25})$ is defined to be 25 mag arcsec^{-2}. With these constraints, an increase in R_{25} corresponds to an increase in $I(R)$ for any particular $R > 0$. A galactic size increase of 50% corresponds to a total galactic star formation rate increase of a factor of $1.5^2 = 2$, for the same rate per unit total area. If density-wave–triggered star formation is responsible for this size and rate increase, then the wave's contribution to the total star formation rate in grand design galaxies is $\sim 50\%$.

The observation that the $B-V$ colors of galaxies are independent of arm class implies that the time variation of the star formation rate is independent of the presence of a wave. The $B-V$ colors depend on the relative proportion of stars with different ages. This proportion is apparently independent of triggering from a wave, possibly because the triggering rate has the same long-term time variation in grand design galaxies as does the untriggered star formation rate in flocculent galaxies. If waves trigger star formation, then this result implies that most grand design galaxies have had their waves for a long time, and that most flocculent galaxies have been without a wave for a long time. The time scale for the appearance and disappearance of triggering waves must be longer than several times 10^9 yr, because this is the time period during which $B-V$ colors of star-forming regions change the most rapidly. Short-time variations of triggering waves would make grand design galaxies bluer than flocculent galaxies, just as the interacting galaxies studied by Larson and Tinsley (1978) are bluer than noninteracting galaxies.

Another explanation for the lack of an obvious correlation between the star formation rate and the presence of a density wave is that the star formation rate is determined only by the rate at which gas is added to or recycled in the galactic disk (Seiden, private communication). Any of a variety of star formation mechanisms, including density wave triggering and other stimulated processes, and spontaneous star formation of various types, could continuously convert all of the gas in excess of a critical density into stars at whatever rate balances the gas input rate. The present results then suggest that the gas accretion or recycling rate is independent of the presence of a density wave mode, which is probably not unreasonable. If density waves are present in a galaxy, they could contribute to the triggering of star formation; if they are not present, the deficit in wave triggering could be offset by a greater rate of triggering from some other process.

The lack of an obvious correlation between the average star formation rates in most galaxies and the presence of density waves does not rule out the possibility that density waves trigger a small amount of star formation in all grand design galaxies, and that density waves trigger a large amount of star formation in rare cases. A small amount of direct wave triggering would not be noticed in the present study. The rms deviation in the star formation rate per unit area can be used to place a limit on the fraction of star formation in a typical galaxy that directly correlates with the presence of a wave mode. The scatter of points in Figure 1 allows the star formation rate in grand design galaxies to exceed that in flocculent galaxies by at most a factor of ~ 2. Thus density waves could possibly contribute 50% to the total star formation rates in galaxies with grand design structures. This is consistent with the other limits on wave-triggered star formation derived in this paper. Of course the scatter in Figure 1 also allows grand design galaxies to contain less star formation than flocculent galaxies, by the same factor.

Galaxies with a larger amount of triggering could be too rare to be included in the present sample. Substantial triggering may occur only in galaxies with unusually strong density wave shocks. Such galaxies might be interacting, for example, with strong stellar waves or orbit perturbations in their disks, or strong wave-induced dissipation of orbital energy leading to mass inflow into the nuclei. They might also be barred galaxies (or barred Magellanic-type irregular galaxies) because the shock strength is probably large near the ends of the bars (Roberts, Huntley, and van Albada 1979), and because the nuclear regions of these galaxies sometimes contain tiny spirals with prominent star formation (Sandage 1961; Wakamatsu and Nishida 1980; Sanders and Tubbs 1980; Hawarden *et al.* 1986). The amplitudes of density waves in galaxies with unusually large star formation rates, such as interacting galaxies, some barred galaxies, infrared galaxies observed by *IRAS* (e.g., Soifer *et al.* 1984), star-burst galaxies, and so on, should be compared to the amplitudes of waves in normal galaxies to determine the possible influence of wave-triggered star formation in these extreme cases.

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