1983ApJ...267..563H

THE ASTROPHYSICAL JOURNAL, 267:563–570, 1983 April 15
© 1983. The American Astronomical Society. All rights reserved. Printed in U.S.A.

# THE RADIAL DISTRIBUTION OF H II REGIONS IN SPIRAL GALAXIES

P. W. HODGE[1]
University of Washington
AND
R. C. KENNICUTT, JR.[1]
University of Minnesota
*Received 1982 July 19; accepted 1982 October 12*

## ABSTRACT

We have examined the radial distribution of H II regions in the rectified planes of 37 galaxies. They group themselves into three broad classes: those with continually decreasing density outward, those with oscillating density, and those with doughnut-shaped density distributions. Generally, the second class is made up largely of SB galaxies, and the last is mostly populated by early Hubble types. A correlation is also found with absolute magnitude, which increases along the sequence given above. Most galaxies' outer H II region distributions show an exponential decrease in density, with a slope that is strongly correlated with Hubble type and absolute magnitude. We also find a correlation between Hubble type and the size of H II region density fluctuations, in the sense that later Hubble types show smaller differences in H II region density.

*Subject headings:* galaxies: structure — nebulae: H II regions

## I. INTRODUCTION

One of the important elements in the study of the evolution of galaxies is the location in the galactic disk of star formation events; how does this location vary with the physical characteristics of galaxies and with time? Only for the very nearest galaxies can one determine star formation patterns as a function of time (e.g., as with star clusters), but for other galaxies it is possible to at least establish the pattern of current star formation; one of the more straightforward ways of doing so is to examine the distribution of H II regions in galaxies.

This is one of a series of papers that examine the galaxy-wide distribution of H II regions using a recently compiled catalog of H II regions in 125 galaxies (Hodge and Kennicutt 1982). Other papers have dealt with a comparison with spiral arm theory predictions (Kennicutt and Hodge 1982), an analysis of spiral arm shapes (Kennicutt 1982*a*), and a study of arm widths (Kennicutt 1982*b*). This paper examines the global distribution of H II regions, with an emphasis on the variation of the H II region number density with distance from the center of the galaxy.

In a previous study of this topic, based on fewer galaxies and shallower surveys (Hodge 1969*a*, *b*), it was found that each Hubble type seemed to show a different characteristic pattern of H II region distributions, with early Hubble types showing a narrower, "ring-shaped" distribution, and later types averaging a less steep, monotonically decreasing distribution. Mean curves for different Hubble types were obtained, but it was apparent that a considerable variation existed, even for morphologically similar galaxies. The purpose of this paper is to examine this question further with more complete data.

A study of similar data for four galaxies, carried out with the same goals but using a very different approach for the analysis, has been published by Considere and Athanassoula (1982). In their exhaustive paper on M33, Boulesteix *et al.* (1974) compared the radial distribution of its H II regions with that of several other astrophysical components of that galaxy.

## II. OBSERVATIONS

The plate material used for this study has been described elsewhere (Hodge and Kennicutt 1982). It consists of narrow-band (20 Å) Hα photographs and matching off-Hα plates, taken with the Kitt Peak National Observatory's 2.1 m and 0.9 m telescopes. Positions of H II regions were measured with a digitizer and, considering all sources of error and uncertainty as described in the paper cited, are reliable to $\sim \pm 3''$. In that paper, we give complete maps and tables of positions for the H II regions in the galaxies of this study.

For the purposes of this paper, we chose 34 spiral galaxies in our sample that had at least 50 H II regions

[1]Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.



© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H



TABLE 1

GALAXIES OF THIS SURVEY[a]

| Galaxy | Type | $M_B$ | Number H II | Inclination Angle | P.A. | Type | $\alpha^{-1}$ H II (kpc) | $\alpha^{-1}$ Starlight (kpc) | Source |
|---|---|---|---|---|---|---|---|---|---|
| NGC 157 ... | Sc | −22.2 | 84 | 41° | 72° | Y | 4.6 | 2.6 | 1 |
| 428 ... | Sc | −20.6 | 58 | 53 | 123 | Y | 3.6 | ... | |
| 470 ... | Sbc | −21.5 | 51 | 66 | 152 | Z | 3.1 | ... | |
| 772 ... | Sb | −23.3 | 62 | 42 | 126 | X | 11.0 | ... | |
| 925 | SBc | −21.1 | 132 | 35 | 128 | X–Y | (4.0) | ... | |
| 1073 ... | SBc | −20.9 | 74 | 68 | 0 | Y | (3.5) | ... | |
| 1232 ... | Sc | −22.6 | 529 | 82 | 89 | Z | 9.1 | ... | |
| 1832 ... | SBb | −21.5 | 57 | 44 | 5 | Z | 3.3 | ... | |
| 2276 ... | Sc | −22.1 | 72 | 73 | 58 | Z | 7.1 | 5.1 | 2 |
| 2403 ... | Sc | −19.5 | 605 | 36 | 125 | X | 2.0 | 1.5 | 3 |
| 2500 ... | Sc | −18.7 | 64 | 66 | 85 | Z | 0.8 | ... | |
| 2805 ... | (Sd) | (−21.0) | 118 | 54 | 140 | X–Y | 15.2 | ... | |
| 2835 ... | SBc | −20.2 | 125 | 42 | 60 | Y | (3.2) | ... | |
| 2841 ... | Sb | −21.5 | 61 | 25 | 146 | Z | (2.6) | 5.4 | 4 |
| 2976 ... | Sd | −17.5 | 74 | 42 | 60 | Y | 0.5 | ... | |
| 3031 ... | Sb | −20.8 | 801 | 31 | 154 | Z | (1.0) | 3.0 | 5 |
| 3184 | Sc | −20.3 | 144 | 66 | 159 | Y | 2.8 | ... | |
| 3239 ... | (SBd) | (−18.5) | 91 | 35 | 75 | X | (2.3) | ... | |
| 3310 ... | Sbc pec | −20.8 | 86 | 59 | 140 | X | 2.5 | ... | |
| 3447 ... | (Sd) | ... | 66 | 78 | 82 | Y | 0.2 | ... | |
| 3486 ... | Sc | −20.0 | 153 | 51 | 88 | Z | (2.5) | ... | |
| 3521 ... | Sb | −21.6 | 149 | 24 | 164 | Z | (2.3) | 1.3 | 6 |
| 3938 ... | Sc | −20.5 | 160 | 80 | 80 | Z | 3.3 | 3.1 | 7 |
| 4303 ... | (SBc) | −21.8 | 289 | 85 | 7 | Z | (5.4) | 7.0 | 8 |
| 4321 ... | Sc | −21.9 | 286 | 59 | 86 | X–Y | (5.6) | 7.0 | 8 |
| 4559 ... | Sc | −21.2 | 78 | 25 | 150 | Z | 5.6 | ... | |
| 5055 ... | Sbc | −21.3 | 138 | 31 | 99 | Z | 3.0 | 2.5 | 9 |
| 5204 ... | Sd | −18.1 | 60 | 31 | 157 | Z | 1.6 | ... | |
| 6015 ... | Sc | −20.5 | 105 | 25 | 39 | Z | (3.0) | ... | |
| 6946 ... | Sc | −20.3 | 540 | 59 | 52 | X | (1.5) | 2.6 | 10 |
| 7331 ... | Sb | −22.6 | 124 | 21 | 165 | Z | 7.4 | 8.6 | 4 |
| 7479 ... | SBbc | −22.3 | 66 | 54 | 36 | Z | 7.3 | 7.1 | 11 |
| 7741 ... | SBc | −20.2 | 85 | 44 | 160 | Y | (4.5) | ... | |
| IC 342........ | (Scd) | (−19.1) | 666 | 80 | 85 | X–Y | (6.3) | 3.7 | 10 |

[a]Hubble types, absolute magnitudes, and distances are from Sandage and Tammann 1981, except those in parentheses, which were calculated or classified by the authors. Values for $\alpha^{-1}$ in parentheses are explained in the text.

SOURCES.—(1) Blackman 1979*a*. (2) Shakbazyan 1973. (3) Okamura, Takase, and Kodaira 1977. (4) Boroson 1981. (5) Guidoni, Messi, and Natali 1981. (6) Blackman 1979*b*. (7) van der Kruit and Shostak 1982. (8) Fraser 1977. (9) Fish 1961. (10) Ables 1971. (11) Okamura 1978.

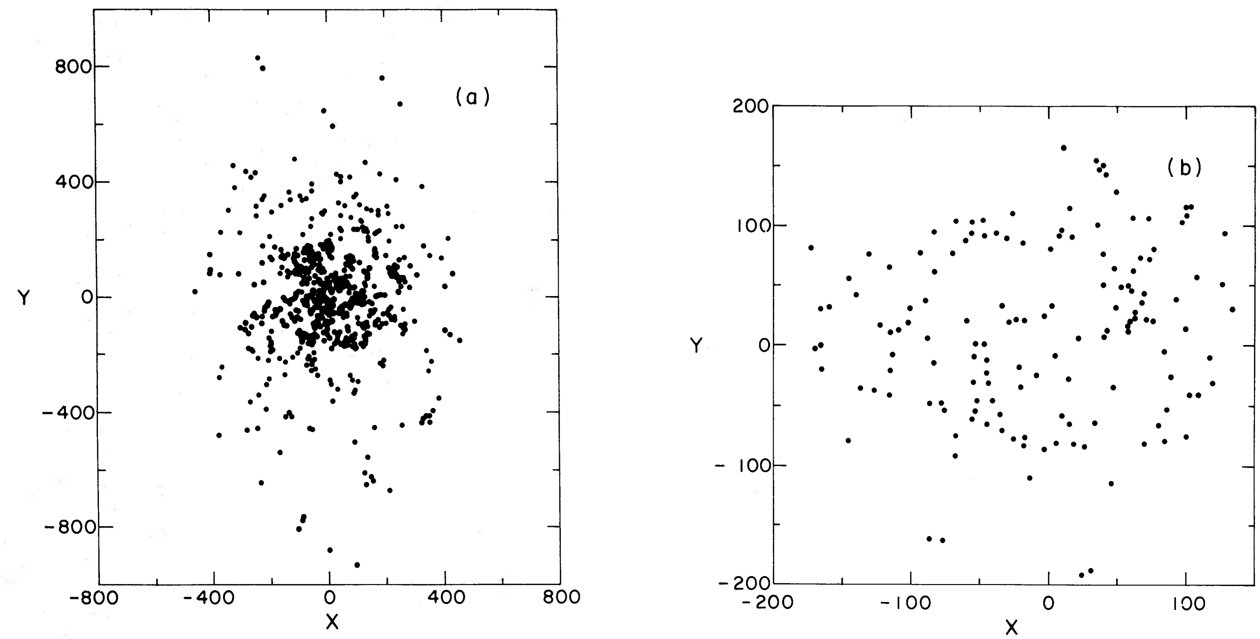
mapped and that had inclinations (measured with respect to the line of sight) of at least ~ 30°. We rectified the maps to face-on by using the inclination angles and position angles published by Danver (1942) for the 12 in common with his list and from published large-scale white-light photographs (e.g., Sandage 1961) for 16 additional objects. For the remainder of the galaxies, we solved for the inclination angle by fitting the H II region number density profile along the major axis to that along the minor axis by least squares and found the major axis by solving for the best-fit least-squares line passing through the nucleus and the H II regions. Table 1 lists the galaxies chosen and gives their derived properties, and Figure 1 shows examples of face-on plots. Data for three additional galaxies, NGC 628 (Hodge and Kennicutt 1976), NGC 3631 (Boeshaar and Hodge 1977), and M31 (Pellet *et al.* 1978), are also included in the discussion below.

It should be noted that the efficiency of detection of H II regions in this survey is relatively uniform because the narrowness of the Hα filters cuts out almost all of the stellar radiation, unlike the case for the data used in the 1969 discussions (Hodge 1969*a*, *b*), which were affected by the fact that the centers of the images of some of the galaxies were burned out. Also, we do not expect that our derived radial distributions are sensitive to our conventions with regard to what we define as an H II region, since our detailed photometry of NGC 628's H II regions showed no radial dependence in their structural properties (Kennicutt and Hodge 1982).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H





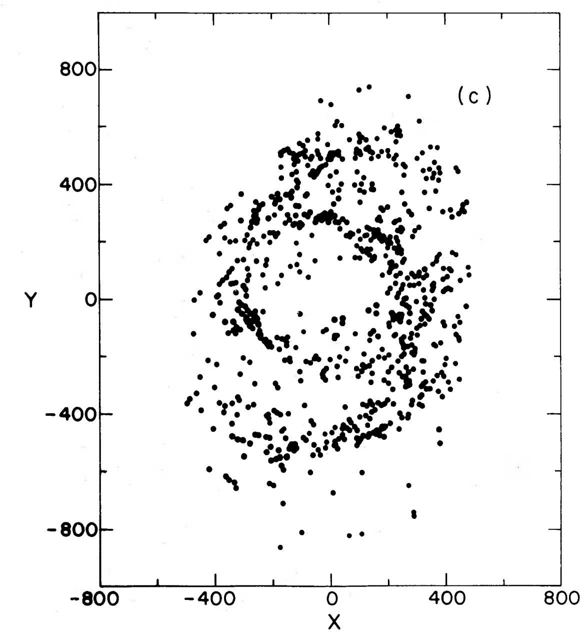




FIG. 1.—Rectified face-on maps of the H II regions in three representative galaxies: (*a*) NGC 2403, (*b*) NGC 3184, and (*c*) NGC 3031.

## III. RESULTS

Figure 2 shows examples of the complete radial density profiles, illustrating the variety of shapes encountered in the sample. Although there exists a continuum of different shapes among the curves, there is enough of a pattern to allow separation into three broad classes, exemplified by the three samples shown in Figure 2. We have classified the curves according to the following convention, entering the class in Table 1:

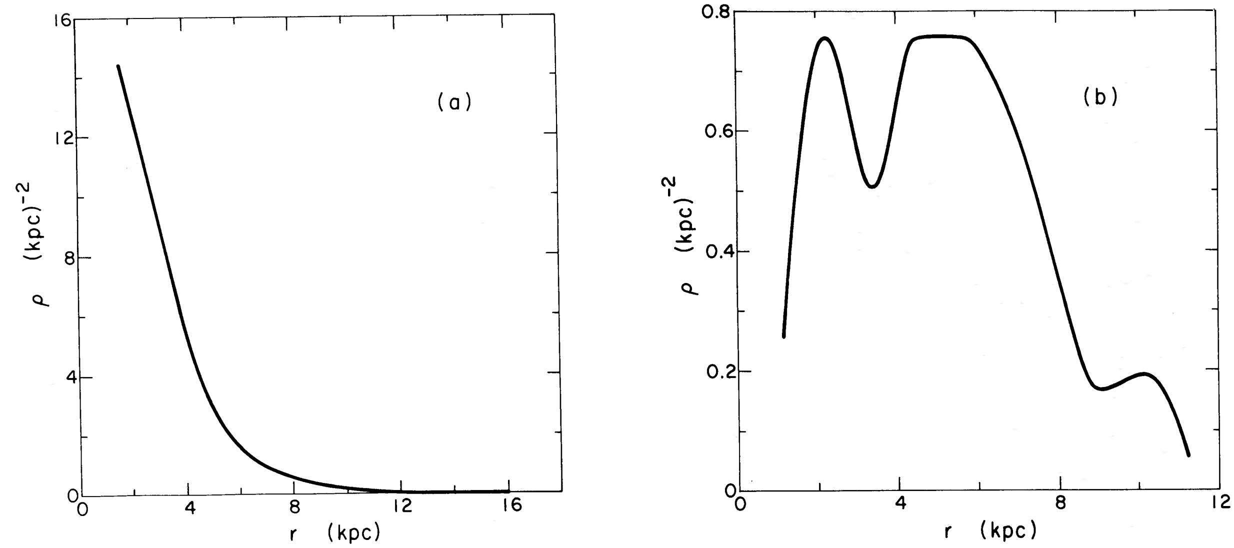
| Class | Description |
|---|---|
| X | Continually decreasing density outward from center |
| Y | Oscillating, decreasing density outward |
| Z | Ring-shaped, with deep minimum central area |

In order to understand what physical effect might be involved in these differences, we sought any correlation of type with other gross properties of the galaxies. For instance, Figure 3 shows the distribution among radial density classes for early and late Hubble types, showing a conspicuous difference: all but one of the early Hubble-type galaxies are of class Z, while the later Hubble-type galaxies are more spread out, with the majority being of class Y. A second relationship shows up in Figure 4, which illustrates the difference in the classes for Sc and SBc galaxies. All of the barred samples are of class Y or X–Y, while the unbarred Sc galaxies show a wide spread, with the majority being class Z. A third relationship shows up when the average absolute magnitudes are calculated for the difference classes: for X, $M_B = -19.9 \pm 0.5$; for Y, $M_B = -20.5 \pm 1.0$; and for Z, $M_B = -21.2 \pm 0.9$. All distances and absolute magnitudes are adopted from the revised Shapley-Ames catalog (Sandage and Tammann 1981).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H





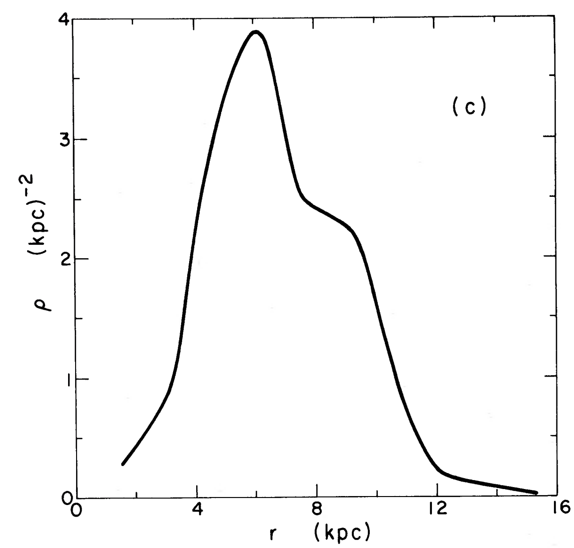




FIG. 2.—Examples of radial distributions of H II regions of the three classes. That for NGC 2403 is of class X, for NGC 3184 is class Y, and NGC 3031 is class Z.

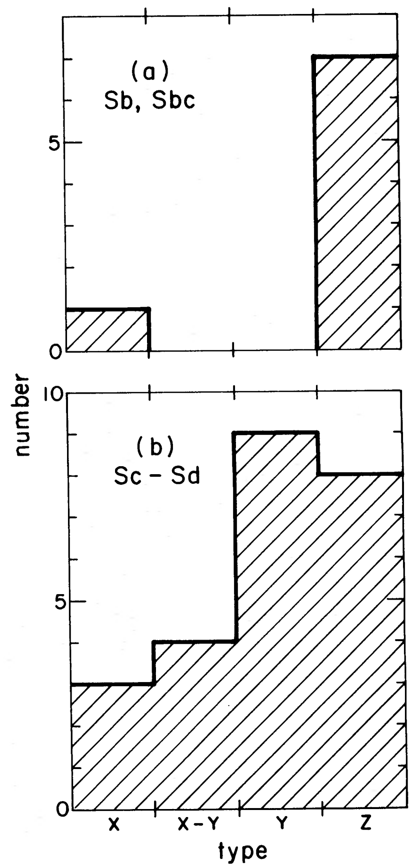



FIG. 3.—Distribution among classes for early and for late Hubble types.

Because the disks of spiral galaxies generally show an exponential luminosity decrease outward, we examined the outer profiles of the H II region density to see if a similar result applies. In order to test this we have plotted the projected mean radial densities of H II regions in galaxies of different Hubble types (Figs. 5, 6, 7, and 8). Only the outer parts of the distributions, beyond the point of maximum, are plotted. Except for the barred galaxies, almost all of the distributions show a reasonably good fit to an exponential decrease outward. For these we have measured the exponential scale

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H



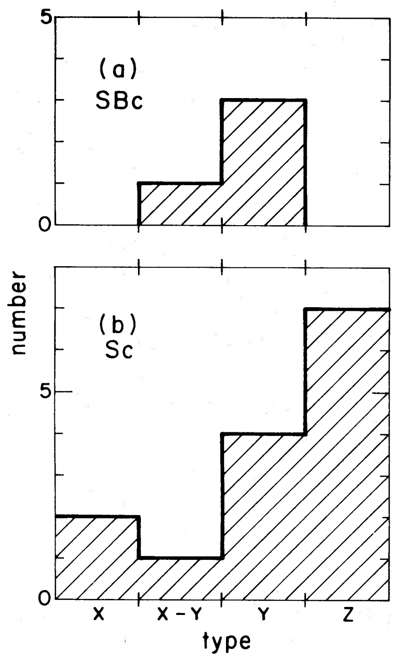



FIG. 4.—Difference in distribution of classes for normal and for barred galaxies.

length, $\alpha^{-1}$ (Freeman 1970) and have entered the results in Table 1. For those cases that are *not* a good fit to an exponential, we have quoted a value of $\alpha^{-1}$ in the table, indicating by parentheses that it is a crude approximation, in all cases made over the outermost part of the data for each galaxy. The two types of galaxy that did not fit an exponential law were barred galaxies, whose density profiles (Fig. 8) were oscillatory, and those Sb galaxies that had class Z distributions, that is, that had their central areas devoid of H II regions (the only exceptions to this rule are NGC 3468, NGC 6015, and NGC 6946).

Because the data in Figures 5–8 are based on a uniform distance scale, it is possible to use them to look for trends. Figure 9 shows several important trends. First, there is a relationship between scale length and absolute magnitude in the sense that brighter galaxies have larger scale lengths. Second, there is a clear separation with absolute magnitude, the earlier Hubble types having smaller scale lengths for a given absolute magnitude. Third, the relationships show approximately straight lines in Figure 9, implying that the relationship between luminosity and scale length is linear. Fourth, the slopes of the lines in Figure 9 are nearly the same, implying that the H II region equivalent of the central extrapolated luminosity is approximately the same for all Hubble types, a fact that agrees with the well-known result from continuum light photometry, which shows that the extrapolated central surface brightness, $B(0)_c$, is almost always nearly the same (Freeman 1970).

These results can be compared directly with the results for the white light distribution in some of the galaxies' disks. Table 1 quotes values of $\alpha^{-1}$ for those galaxies for which appropriate photometry is available in the literature. Figure 10 shows a comparison of the scale lengths of the white light disks and the H II region distributions, and shows that the values tend to agree fairly well. It should be remembered that some of the H II region values of $\alpha^{-1}$ are only approximations (the parentheses in Fig. 10 indicate those for which an exponential was not a good fit) and that the continuum values of $\alpha^{-1}$ are based on a variety of photometric sources, which do not always agree very closely. Therefore, the large spread shown in Figure 10 may not be significant.

The importance of the exponential disk structure of spiral galaxies has been discussed by Freeman (1970),

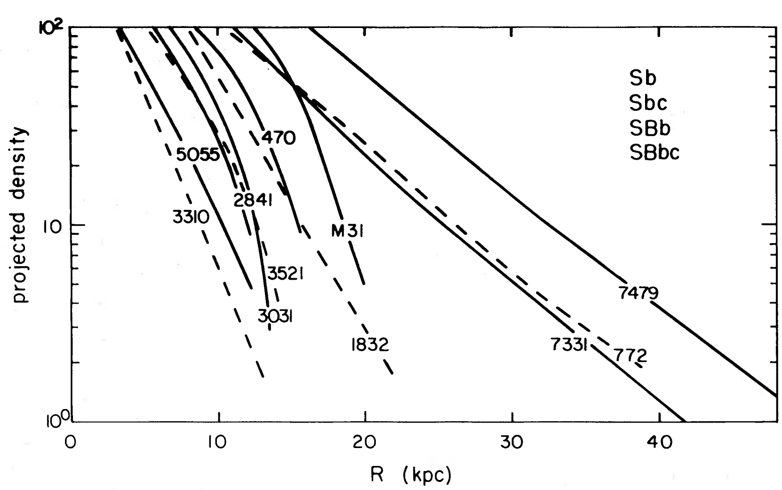



FIG. 5.—Outer H II region density profiles for earlier Hubble types. The density is normalized to 100 at the maximum density.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H

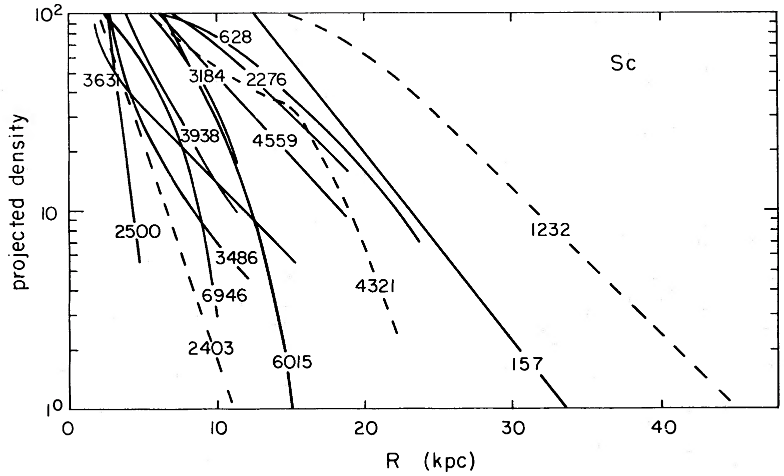



FIG. 6.—As in Fig. 5, but for Sc galaxies

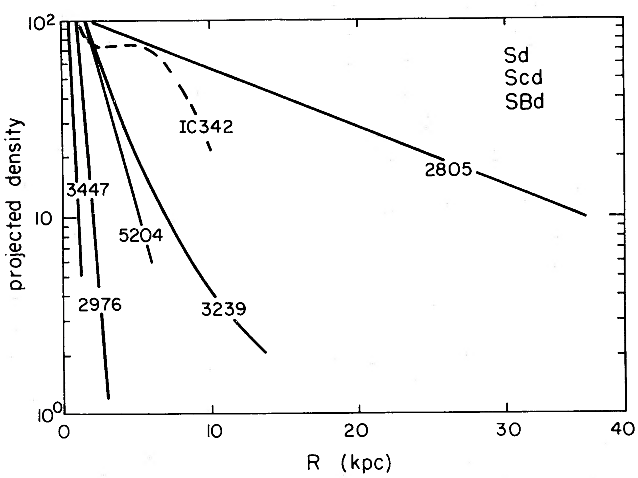



FIG. 7.—As in Fig. 5, but for later Hubble types

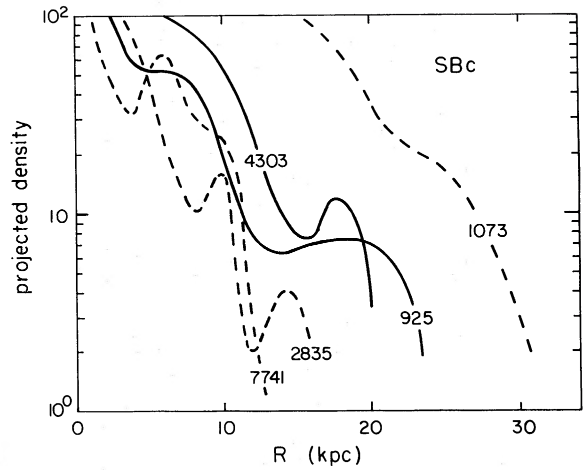



FIG. 8.—As in Fig. 5, but for SBc galaxies

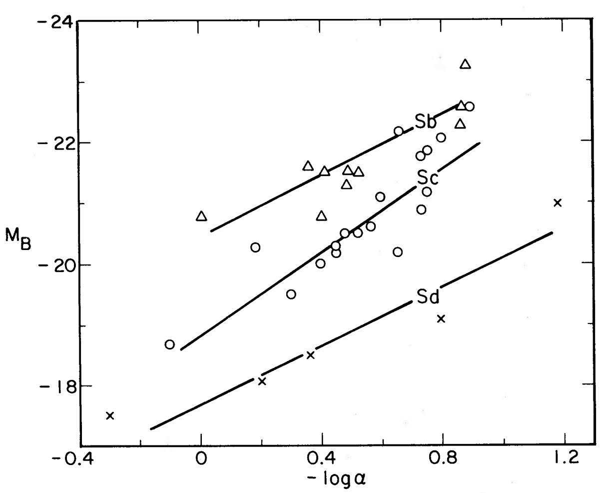



FIG. 9

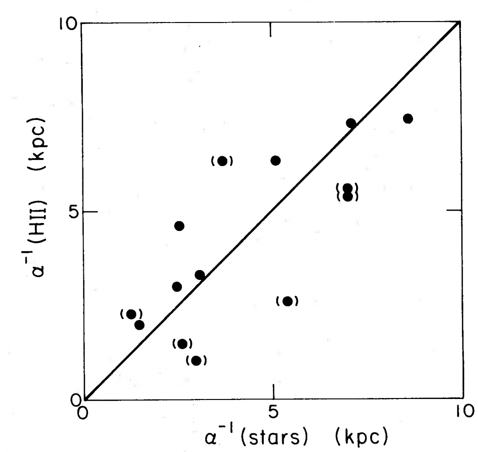



FIG. 10

FIG. 9.—Relationship between the outer exponential scale lengths and the absolute magnitude of the galaxies, as a function of Hubble type. Parentheses indicate approximate fits, as explained in the text.

FIG. 10.—Comparison of scale lengths for H II regions with those for stellar disks, as determined from white-light photometry. Parentheses as in Fig. 9.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H



Sandage, Freeman, and Stokes (1970), Burstein (1979), Strom and Strom (1979), and Boroson (1981). Freeman (1970) found, for example, that the scale lengths of the disks of spiral galaxies show a correlation with absolute magnitude in the same sense as found here for H II regions. However, he did not find a correlation with Hubble type, except to the extent that types Sc and later had predominantly smaller scale lengths. Boroson (1981) also found no correlation, but his sample had rather few later Hubble types. Our positive correlation (Fig. 9) shows up only when absolute magnitude is taken into account. A replotting of Freeman's data does show a segregation in the same sense as in Figure 9, but the correlation is not as perfect, probably because of the very different distribution of both Hubble types and absolute magnitudes.

We believe that the general correspondence observed here between the radial profiles of the young H II region population and the integrated disk light is significant. It suggests a strong continuity between the present disk star formation distribution and the past star formation which is reflected in the giant-dominated old disk. We shall resist the temptation of interpreting this interesting result further at this time; we are in the process of obtaining more accurate data on both the star formation and white light distributions in many of these galaxies in order to examine the correlation between the two in more detail. We note in passing, however, that a correspondence between the exponential behaviors of the H$\alpha$ and integrated disk light has also been observed by DeGioia-Eastwood *et al.* (1981) in NGC 6946 and IC 342. Young and Scoville (1982) have observed a similar correlation between the CO emission and the integrated light in those galaxies, which is perhaps not surprising in view of the results presented above. Similarly the observation by van der Kruit, Allen, and Rots (1977) that the nonthermal radio emission follows an exponential disk may be related to the star formation distribution.

To find any other possibly significant correlations of these data with the galaxies' properties, we determined correlation coefficients for the following: $\bar{r}$ versus $r_{\max}$; $\Delta r/\bar{r}$ versus pitch angle; $\Delta \rho/\bar{\rho}$ versus pitch angle; $\Delta r/\bar{r}$ versus luminosity; $\bar{r}/r_{\max}$ versus luminosity; $\Delta\rho/\bar{\rho}$ versus luminosity; $\bar{r}/r_{\max}$ versus Hubble type; $\Delta r/\bar{r}$ versus Hubble type; $\rho_{\min}/\rho_{\max}$ versus Hubble type; where $\bar{r}$ is the mean of the radial distance of all H II regions, $r_{\max}$ is the radial distance of the most distant H II region, $\Delta r$ is the standard deviation of $\bar{r}$ (a measure of the spread of $r$), $\bar{\rho}$ is the mean density of H II regions per kpc$^2$ in the galaxy plane, $\Delta\rho$ is the standard deviation of $\bar{\rho}$, $\rho_{\min}$ is the minimum density inside $r_{\max}$, and $\rho_{\max}$ is the maximum density. All but two of these showed no significant correlation. There was a strong relationship (correlation coefficient = 0.98) between $\bar{r}$ and $r_{\max}$, a not surprising result that indicates simply that most galaxies have their H II regions fairly smoothly distributed inside their outer boundaries. A weaker correlation (coefficient = 0.59) exists between $\Delta\rho/\bar{\rho}$ and Hubble type in the sense that $\Delta\rho$ (normalized to $\bar{\rho}$) decreases with later types. Thus, the later Hubble types tend to have H II region densities that show smaller fluctuations than do earlier types.

In summary, the most important results of this study are that the radial distributions of H II regions in galaxies show properties that correlate with Hubble type and luminosity. The higher luminosity galaxies of a given type have the larger scale lengths, as might be expected if the density of star forming regions is relatively insensitive to total luminosity. The later Hubble types for a given luminosity also have larger scale lengths, with a clear separation from Sb's to Sd's.

Several questions remain unexplored and will be the subjects of future papers. One of us (R. C. K.) is obtaining white-light disk photometry of many of the galaxies for which we have H II region data, and these will be used for further comparison. Other constituents, such as CO (e.g., Young and Scoville 1982) and far-infrared radiation (Smith 1982) are being mapped for many galaxies of our sample, as are, of course, H I and radio continuum radiation, and these also will be the subject of comparisons, as will various dynamically determined parameters (rotational velocities, pitch angles, and resonances).

We are greatly indebted to the Kitt Peak National Observatory, where these data were obtained, to the former Hale Observatories, where R. C. K. did some of the research, and to the National Science Foundation, which funded part of this work under grant AST81-02952 to P. W. H. and grant 81-11711 to R. C. K. Patrick Lin did the computer reductions, and Victor Morris and Richard Dickson measured H II region positions.

## REFERENCES

Ables, H. 1971, *Pub. US Naval Obs.*, **20**, 4.
Blackman, C. P. 1979*a*, *M.N.R.A.S.*, **186**, 701.
______. 1979*b*, *M.N.R.A.S.*, **188**, 93.
Boeshaar, G., and Hodge, P. 1977, *Ap. J.*, **213**, 361.
Boroson, T. 1981, *Ap. J. Suppl.*, **46**, 177.
Boulesteix, J., Courtes, G., Laval, A., Monnet, G., and Petit. H. 1974, *Astr. Ap.*, **37**, 33.
Burstein, D. 1979, *Ap. J.*, **234**, 435.
Considere, A. A., and Athanassoula, A. 1982, *Astr. Ap.*, in press.
Danver, C. G. 1942, *Ann. Obs. Lund.*, No. 10.
de Gioia-Eastwood, K., Grasdalen, G. L., Strom, S. E., and Strom, K. M. 1981, *Bull. AAS*, **13**, 797.
Fish, R. A. 1961, *Ap. J.*, **134**, 880.
Fraser, C. W. 1977, *Astr. Ap. Suppl.*, **29**, 161.
Freeman, K. C. 1970, *A.J.*, **160**, 811.
Freeman, K., and de Vaucouleurs, G. 1970, *Acad. K.I.A.*, **1**, 1.
Guidoni, U., Messi, R., and Natali, G. 1981, *Astr. Ap.*, **96**, 215.
Hodge, P. 1969*a*, *Ap. J.*, **155**, 417.
______. 1969*b*, *Ap. J.*, **156**, 847.
Hodge, P., and Kennicutt, R. C., Jr. 1976, *Ap. J.*, **207**, 36.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...267..563H



Hodge, P., and Kennicutt, R. C., Jr. 1982, *A.J.*, submitted.
Kennicutt, R. C. 1982*a*, *Ap. J.*, **259**, 530.
______. 1982*b*, *Ap. J.*, in press
Kennicutt, R. C., and Hodge, P. 1982, *Ap. J.*, **253**, 101.
Okamura, S. 1978, *Pub. Astr. Soc. Japan*, **30**, 91.
Okamura, S., Takase, B., and Kodaira, K. 1977, *Pub. Astr. Soc. Japan*, **29**, 567.
Pellet, A., Astier, N., Viale, A., Courtes, G., Maucherat, G., Monnet, G., and Simien, F. 1978, *Astr. Ap. Suppl.*, **31**, 439.
Sandage, A. R. 1961, *The Hubble Atlas of Galaxies* (Washington, DC: Carnegie Institute).
Sandage, A. R., Freeman, K. C. and Stokes, N. R. 1970, *Ap. J.*, **160**, 831.
Sandage, A. R., and Tammann, G. A. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies* (Washington, DC: Carnegie Institute).
Shakhbazyan, R. K. 1973, *Astrofizika*, **9**, 21.
Smith, J. 1982, personal communication.
Strom, S., and Strom, K. 1979, in *IAU Symposium 84, The Large-Scale Characteristics of the Galaxy*, ed. W. B. Burton (Dordrecht: Reidel), p. 9.
van der Kruit, P. C., Allen, R. J., and Rots, A. H. 1977, *Astr. Ap.*, **55**, 421.
van der Kruit, P. C., and Shostak, G. 1982, *Astr. Ap.*, **105**, 351.
Young, J., and Scoville, N. 1982, *Ap. J.*, **258**, 467.

P. W. Hodge: Astronomy Department, FM-20, University of Washington, Seattle, WA 98195

R. C. Kennicutt: Department of Astronomy, University of Minnesota, Minneapolis, MN 55455

© American Astronomical Society • Provided by the NASA Astrophysics Data System