Barred Galaxies
ASP Conference Series, Vol. 91, 1996
R. Buta, D. A. Crocker, and B. G. Elmegreen, eds.

Star Formation in Barred Galaxies

Andrew C. Phillips

UCO/Lick Observatory, Univ. of California, Santa Cruz, 95060

Abstract. Star formation in barred spirals is discussed, including star formation rates, distribution of H II regions, and H II region luminosity functions. In general, global star formation rates and other properties are consistent with non-barred spirals of comparable Hubble class. In barred spirals of intermediate class (SBb–SBc), the effects of the bar on star formation is clearly seen in the distribution of star forming sites. Two patterns emerge, one that shows star formation concentrated in ring-like zones corresponding to inner and nuclear rings (earlier types) and one that shows star formation concentrated in the bar itself (later types). These properties appear to be well-correlated with both Hubble stage and bar type.

1. Introduction

The location and extent of star formation in barred galaxies, and how they compare to non-barred galaxies, can provide observational insight into astrophysical processes that take place in barred galaxies. Such observations also provide constraints for models seeking to understand both those processes and how barred galaxies evolve.

Several related topics are discussed by others in these proceedings. For example, IR properties, which are intimately tied to star formation, are discussed by Tim Hawarden; H II region conditions and abundances are discussed by J.-R. Roy and by P. Martin. I will limit my discussion primarily to Hα observations of barred galaxies, much of it based on my dissertation survey of nearby barred spirals (Phillips 1993). For a broader overview of this entire subject, I recommend the excellent review article by Kennicutt (1994).

Please note that the term "star formation," as used in this paper, refers to massive stars capable of ionizing hydrogen; extrapolation to total star formation rate implies we know the form of the (constant) IMF. Also note that "barred galaxies" as used here generally refers to strongly-barred spirals.

2. Distribution of Star Forming Sites

Barred galaxies show a wide diversity in their H II region distributions dependent on their morphological class. Figure 1 shows a few representative examples imaged in Hα. The first four galaxies are well-matched in luminosity, and

https://doi.org/10.1017/S025292110004940X Published online by Cambridge University Press

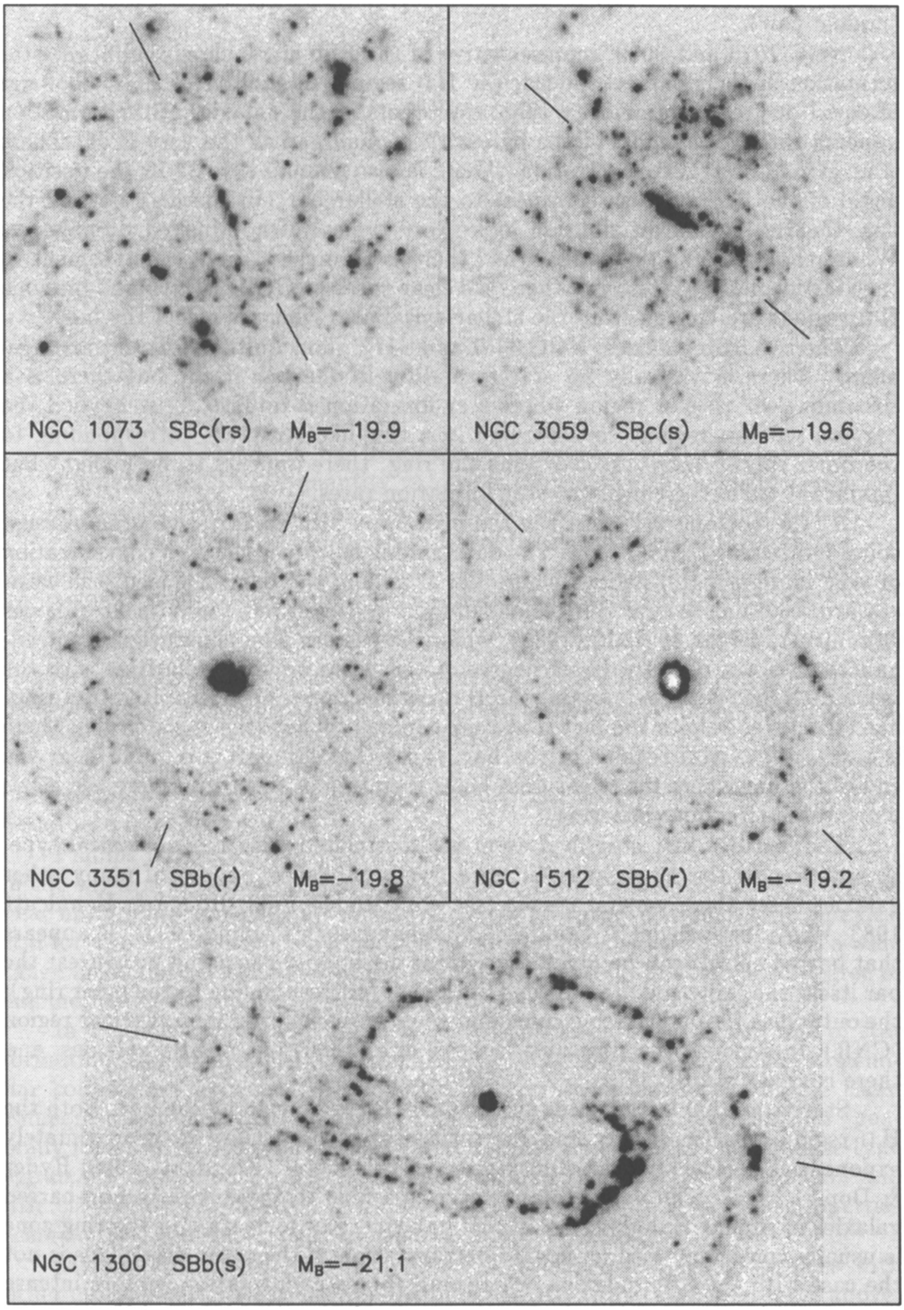

Figure 1. A sampling of barred galaxies in continuum-subtracted Hα. The orientation of the stellar bar is indicated. (Phillips 1993)

https://doi.org/10.1017/S025292110004940X Published online by Cambridge University Press

demonstrate the different distributions seen in SBc (top pair) and SBb galaxies (middle pair).

NGC 1073 and 3059, representative of the SBc class, show significant star formation in their bars — indeed, the H II regions in the bar of NGC 3059 are of equal or greater luminosity than any others in the galaxies. Star formation appears throughout most of the bar, with a small gap at the very ends. There is no strong central concentration. There is also a small "twist" in the position angle of the Hα "bar" with respect to the stellar bar. In the disk beyond the bar, the H II region distribution looks very typical of non-barred Sc galaxies. Where the bar joins the spiral arms, there is at most a slight enhancement in the star-formation rates, and there are clear cases (NGC 1073) where luminous H II regions are lacking from the stellar spiral arm where it meets the bar.

The two SBb galaxies, NGC 3351 and 1512, show quite a different arrangement. There is virtually no star formation in the bar itself, but there is a circumnuclear ring or region where star formation is intense. Just beyond the bar, we see H II regions concentrated in a ring-like structure corresponding to the inner ring. Where the bar joins the ring, there appears to be a slight but significant enhancement in the star formation rates.

At the bottom of Figure 1 is the prototype SBb galaxy with grand-design spiral morphology, NGC 1300. The outstanding feature is the high concentration of very luminous H II regions where the arms join the bar — indeed, the western arm contains several H II regions of luminosities rarely found in Sb galaxies (Kennicutt, Edgar & Hodge 1989), while the eastern arm shows significant enhancements but of much lesser degree. Otherwise, we see similarities with the two SBb galaxies above. Again, the H II regions appear concentrated in a ring-like structure, despite the fact that they generally follow the spiral arms. There is a scarcity of H II regions in the bar; those that do exist are found near the end of the bar where the linear dust lanes turn to join the arm. There is a small but intense circumnuclear ring.

The features just described seem well-correlated with morphological type. In addition to the 15 galaxies in my survey, published images of many other galaxies show these general trends (see *e.g.*, Hodge 1969; Hodge & Kennicutt 1983; Wray 1988; Ryder & Dopita 1993; references in Phillips 1993). It appears that barred spirals can be divided into four distinct star-forming provinces: the bar itself; the "ring zone" at the end of the bar (corresponding to the inner ring); the outer disk beyond the ring zone; and where it exists, the circumnuclear region (CNR). In general, the ring zone is weak or non-existent in SBc galaxies, and there is rarely a CNR.

Star formation in the outer disk appears little affected by the bar. Both the H II region number density and Hα surface brightness show an approximately exponential decline, typical of disk galaxies in general (Kennicutt 1989; Ryder & Dopita 1994). The densities appear comparable to those seen in non-barred galaxies of similar Hubble type. In SBc galaxies, star formation in the ring zone is usually consistent with an inward extrapolation of the outer disk. This is not the case with the SBb galaxies, where ring zone star formation is more intense than would be expected by a factor of order 3. Within the radius of the bar, the azimuthally-averaged H II region and Hα surface densities *drop* by an order of magnitude in the SBb galaxies; in the SBc's, they are approximately the same

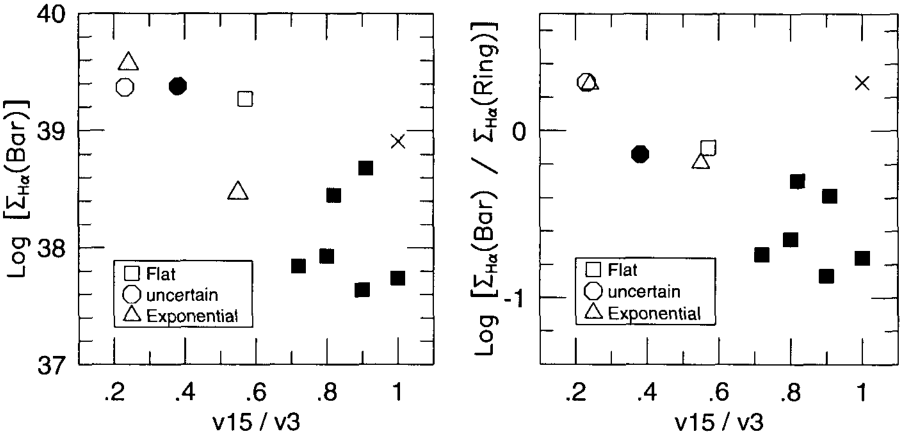

Figure 2. Trends in bar Hα surface brightness (*left*) and bar/ring contrast (*right*). The quantity v15/v3 is the ratio of the velocity curve at $R_{25}/15$, typically just outside the CNR, and at $R_{25}/3$, typically near the end of the bar. This simple index of the velocity curve through the bar has a value of 0.2 for constant angular velocity, and 1.0 for a flat velocity curve. Filled symbols denote galaxies with CNR hotspots.

as the values in the ring zone on the average. This difference in bar/ring/disk behavior between Hubble types is partly responsible for the reciprocal bar/ring relation suggested by Ryder & Dopita (1993).

In all cases, the Hα surface brightness of the CNRs are at least an order of magnitude higher than in any other zone. The CNRs are discussed in more detail in a later section.

Phillips (1993) also attempted to quantify the star formation enhancement in the bar-arm transition regions. SBb galaxies show enhancements by factors of near unity (that is, small) up to $\sim$3. At the bar/arm transition in SBc galaxies, star formation rates show slight enhancements *on the average*, but there is a wide range including several cases where the rates appear suppressed. The degree of enhancement often differs greatly between the two ends of the bar.

In summary, there appears to be a correlation between certain sets of star formation properties and the morphological type of the galaxy. There are similar correlations between the properties of the stellar bars and Hubble class. Elmegreen & Elmegreen (1985) found two distinct bar types: the "flat bar" generally found in earlier-type spirals, and the small "exponential" bars in late-type spirals. Both the bar properties and star formation properties for the SBb and SBc classes are summarized in Table 1. In addition, note that some properties seem to form sequences such as those shown in Figure 2.

My survey included only SBb and SBc galaxies. Images of galaxies with other morphological types may be found in the literature (*e.g.,* references above) and also show clear trends with Hubble class. SBbc galaxies typically have strong star formation in *both* the ring zone and the bar; they usually also have a compact zone of vigorous CNR star formation. NGC 1187 and 7479 are good examples. Barred galaxies earlier than type SBb tend to show star formation in rings but neither in the bar nor the center. Very late types (SBm) usually display many H II regions in their bars, but of intermediate luminosity only.

Table 1. Bar & Star Formation Properties

	SBb	SBc
Bar Properties:		
Bar Type	Flat	Exponential
Vel. Curve in Bar	Flat	Rising
Dust lanes / form	Yes/linear	?
Star Formation Properties:		
H II Region Ring	Yes	No/Weak
SF in Bar:	No/Weak	Yes
	(near ends)	Gap at ends
	—	Hα "twist" wrt bar
Bar/Arm Enhance.	Strong–Mod.	Weak–none
CNR "Hotspots"	Yes	No
Luminosity Functions (by zone):		
Disk	Type I	Type I
	$\alpha \lesssim$ Sb	$\alpha \sim$ Sc
Ring	Type II	same as disk
	(crowding prob.?)	
Bar	Steeper than disk	(Shallower than disk)
		(crowding prob.?)

3. H II Region Luminosity Functions

H II region luminosity functions (LFs) are a diagnostic tool which is not yet well-developed, but which potentially gives information about the mass spectrum of Giant Molecular Clouds (GMCs) from which stars form. Extragalactic H II regions we observe are ionized by at least a few — sometimes hundreds or thousands — of O stars. Their Hα luminosity thus reflects the number of O stars, which in turn scales with the cluster mass, which presumably scales with the mass of the progenitor GMC. Thus, the H II region LF should reflect the underlying mass spectrum of the GMCs.

Many observers, and most notably Kennicutt, Edgar & Hodge (1989; hereafter KEH) have shown that H II region LFs typically have simple power-law (Type I) forms. A few have a more complicated broken-power-law form (Type II), with a shallow slope at low luminosities and a steep slope above some break-point. This latter form has been interpreted as reflecting conditions which tilt the mass spectrum to higher-mass GMCs — but only up to a point, above which

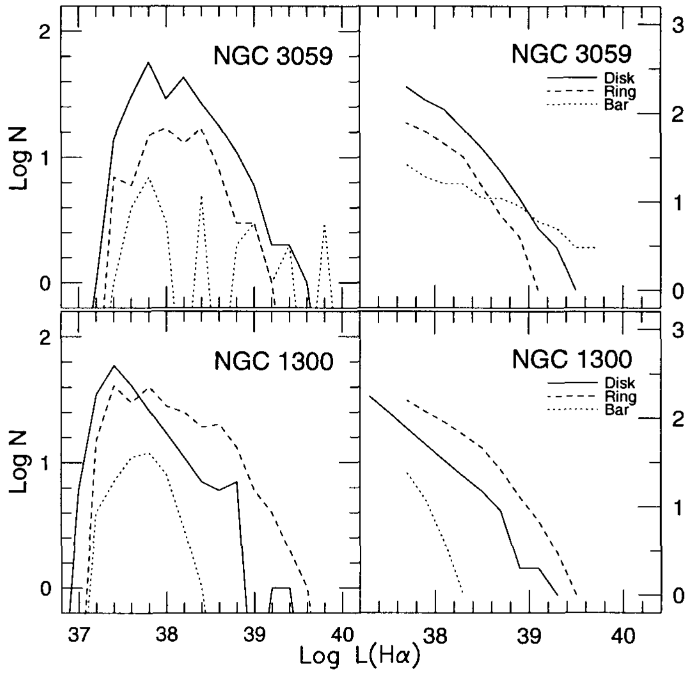

Figure 3. Differential (left) and cumulative Hα luminosity functions of two representative cases, NGC 3059 (SBc) and NGC 1300 (SBb), divided by zone. Only those luminosities where the counts are believed to be complete are plotted in the cumulative LFs. (Phillips 1993)

cloud growth is severely suppressed. KEH showed that ~80% of galaxies have simple Type I LFs. The slopes are steepest in the earlier Hubble types, with values implying that most stars are formed in small clusters. At the other extreme (Sm and Im) the shallow slopes indicate most stars form in huge complexes like 30 Dor. Intermediate Hubble types have corresponding intermediate slopes. Among barred galaxies, LFs measured by various researchers show a similar range in form and power-law slopes, and comparable trends with Hubble type.

Of particular interest is how LFs vary *within* a barred galaxy – *i.e.,* how do the LFs in the bar, "ring zone" and outer disk compare, and what can this tell us about different conditions in these regions? Figure 3 shows differential and cumulative LFs for two representative cases. NGC 3059 (SBc) shows Type I forms with similar slopes in both outer disk and ring zone. This supports the conclusion that there is little difference between these two zones in SBc galaxies. For the bar, the measurements are difficult due to blending/crowding, but the LF appears to be much shallower — the slope is similar to those in the latest type galaxies, which generally have dynamically quiet environments.

NGC 1300 (SBb) shows something quite different. The outer disk has a Type I form (best seen in the cumulative LF), but the ring zone shows a clear Type II break. This may imply that in the ring zone there is a preferred

GMC mass, above which either cloud growth is suppressed or massive clouds are rapidly disrupted. In the bar, on the other hand, the relatively steep LF slope indicates stars form only in relatively small clusters — here the environment apparently does not permit the growth of truly massive GMCs. Hydrodynamical models suggest strong shock velocities (Tubbs 1980) or shear (Athanassoula 1992) are likely mechanisms.

In summary, we see once again a difference in star formation properties between earlier- and later-type barred spirals; these are also listed in Table 1. Note that the circumnuclear LFs appear shallow, but severe crowding and blending of H II regions, as well a severe patchy obscuration, make this an extremely tentative result. Luminosity functions of the ionizing clusters themselves, measured from high-resolution HST images, will provide a much more accurate answer.

4. Circumnuclear Star Formation

The association of bars with vigorous circumnuclear star formation is now widely accepted. It was recognized almost from the time of Morgan's (1958) classification of "hotspot" nuclei, and Sérsic & Pastoriza (1965, 1967) concluded that *all* such hotspot nuclei were found in strongly- or weakly-barred galaxies. Early radio-continuum studies showed strong emission from the centers of some large barred spirals. Hawarden *et al.* (1986) found a striking correlation between a "warm" 25μm excess and the presence of a bar, which was attributed to strong circumnuclear star formation in a large fraction of barred galaxies. Devereux (1987) followed Hawarden *et al.*'s finding by showing that, among luminous galaxies, $\sim$40% of barred spirals of type SBbc or earlier display a strong 10μm enhancement in the inner few arcsec compared to non-barred galaxies. Such enhancements are somewhat rarer in later-type spirals, where there is no clear preference for barred vs. non-barred types.

One of the surprises in my own survey was the ubiquity of strong CNR star formation: eleven of twelve SBb galaxies observed in a partially complete sample from the RSA show this phenomenon. Many other examples exist in the literature, but I know of only one other case, NGC 3992, which does not display CNR Hα (Cepa & Beckman 1990). Thus, it appears strong CNR star formation is long-lived; if so, we can estimate mass inflow rates from the SFRs. Also, the phenomenon must be nearly as long-lived as the SBb galaxies themselves (*i.e.*, in their current form) which has interesting implications for the evolution of such galaxies.

Unfortunately, the CNRs are very difficult to study, primarily because the heavy and variable dust obscuration strongly modifies the appearance of both the star-forming regions and the underlying stellar population (see excellent examples in Knapen *et al.* 1995, and Ward, Depoy & Aspin 1990).

5. Star Formation Rates

The subject of star formation rates (SFRs) in barred galaxies has been controversial, with some claiming SFRs are strongly enhanced in barred galaxies and others claiming the opposite. In large part, this was probably driven by somewhat anecdotal evidence, *e.g.*, star formation is absent in (some) bars, it is strongly enhanced at (some) bar ends, etc. Excluding the circumnuclear regions, quantitative measurements show *little if any* difference between the SFRs in barred and non-barred galaxies (see Figure 1 in Kennicutt 1994). The real controversy lies in the SFRs for the circumnuclear regions, and here it is basically the uncertainly in the extinction which causes the problem. Typical measurements of Balmer line ratios in individual CNR H II regions show no difference compared to disk H II regions (Kennicutt, Keel & Blaha 1989); but since the extinction is variable this does not give a good measure of the average extinction. Of more value is measurements integrated across the entire CNR, such as those of Osmer, Weedman & Smith (1974), who derived a "single screen" extinction value of typically ~2.5–3 mag at Hα. Again, however, the strong, *patchy* extinction makes this only a lower limit since less-obscured regions contribute more heavily to the averaged line fluxes. Hα/radio continuum ratios may give a better indication. Hummel, van der Hulst & Keel (1987) used such measurements of NGC 1097 and found an average CNR extinction only slightly greater than for disk H II regions; however, large corrections had to be made for estimated contributions from non-thermal radio sources. The most direct reliable result will come from Brγ/Hα ratios, but here the relative weakness of Brγ and the strong background make this a difficult measurement. Forbes, Kotilainen & Moorwood (1994) find extinctions of ~3–4 mag at Hα in NGC 7552 using this method.

Table 2. Circumnuclear Star Formation Rates

	CNR/Total SFR		SFR ($M_\odot$ yr^{-1})		$M(R_{Nuc.Ring})$
NGC	$A_{H\alpha}$=1.1	$A_{H\alpha}$=3.4	$A_{H\alpha}$=1.1	$A_{H\alpha}$=3.4	(10^8 $M_\odot$)
613	.22	.70	1.2	10	12
1300	.07	.37	0.1	1.2	11
1365	.30	.78	3.9	32	67
1433	.11	.50:	0.1	0.9	14
1512	.31:	.79:	0.1	1.2	32
3351	.45	.86	0.4	3.2	15
5236	.14	.58	0.4	3.7	1.7
1808	.67	.94	1.8	15	29
2997	.06	.35:	0.5	4.5	15

To estimate circumnuclear SFRs for the galaxies in my sample, I have calculated the rates from Hα fluxes following Kennicutt (1983), using both the nominal disk extinction value (1.1 mag) and a value representative of the higher range of extinction values (3.4 mag). These are shown in Table 2, along with an estimate of the fraction of total star formation for the galaxy occurring in the CNRs. The table shows that 7 to 45% of the total star formation takes place in the CNRs if the lower extinction value is adopted, or 40 to $\gtrsim$ 80% with the higher value. Circumnuclear star formation is a major or even dominant component to the overall rates in these galaxies.

The table also shows the mass interior to the CNR as estimated from the velocity curves. In a few cases (*e.g.*, NGC 613), it is clear that the star formation

https://doi.org/10.1017/S025292110004940X Published online by Cambridge University Press

rate (if steady) implies mass transport rates high enough to significantly alter the central mass concentration of the galaxy within a few galactic rotations.

6. Conclusion

This talk is basically summarized in Tables 1 and 2.

Acknowledgments. I wish to thank the organizers of this colloquium, both for the invitation to speak and the support they have provided — in addition to which, the meeting has been a lot of fun for me! I also wish to thank Z. Tsvetanov for pointing out that the central Hα in NGC 5643 is not entirely from young stars.

References

Athanassoula, E. 1992, MNRAS, 259, 345

Cepa, J. & Beckman, J. E. 1990, ApJ, 349, 497

Devereux, N. A. 1987, ApJ, 323, 91

Devereux, N. A. & Young, J. S. 1990, ApJ, 350, L25

Elmegreen, B. G. & Elmegreen, D. M. 1985, ApJ, 288, 438

Forbes D. A., Kotilainen, J. K., & Moorwood, A. F. M. 1994, ApJ, 433, L13

Hawarden, T. G., Mountain, C. M., Leggett, S. K., & Puxley, P. J. 1986, MNRAS, 221, 41P

Hodge, P. W. 1969, ApJ, 155, 417

Hodge, P. W. & Kennicutt, R. C. 1983, AJ, 88, 296

Hummel, E., van der Hulst, J. M., & Keel, W. C. 1987, A&A, 172, 32

Kennicutt, R. C. 1983, ApJ, 272, 54

Kennicutt, R. C. 1989, ApJ, 344, 685

Kennicutt, R. C. 1994, in Mass-Transfer Induced Activity in Galaxies, I. Shlosman, New York: Cambridge Univ. Press, 131

Kennicutt, R. C., Edgar, B. K., & Hodge, P. W. 1989 [KEH], ApJ, 337 761

Kennicutt, R. C., Keel, W. C., & Blaha, C. A. 1989, AJ, 97, 1022

Knapen, J. H., Beckman, J. E., Shlosman, I., Peletier, R. F., Heller, C. H., & de Jong, R. S. 1995, ApJ, 443, L73

Morgan, W. W. 1958, PASP, 70, 364

Phillips, A. C. 1993, Ph.D Dissertation, Univ. of Washington, Seattle

Ryder, S. D. & Dopita, M. A. 1993, ApJS, 88, 415

Ryder, S. D. & Dopita, M. A. 1994, ApJ, 430, 142

Sérsic, J. L. & Pastoriza, M. 1965, PASP, 77, 287

Sérsic, J. L. & Pastoriza, M. 1967, PASP, 79, 152

Tubbs, A. D. 1982, ApJ, 255, 458

Ward, M. J., Depoy, D. L., & Aspin, C. 1990, in Astrophysics with Infrared Arrays, R. Elston, ASP Conf. Series, 76

Wray, J. D. 1988, The Color Atlas of Galaxies, New York: Cambridge Univ. Press

Discussion

T. Hawarden: Do your derived circumnuclear SFRs correlate with FIR luminosities?

A. Phillips: Yes. In fact, the higher extinction value was chosen to bring the "hotspot" galaxies onto the Hα vs. L_{FIR} relationship of Devereux & Young (1990).

T. Hawarden: [This bar/circumnuclear-star-formation combination] has to be a cycle, and the process could [result in] the deletion of bars in strongly-barred early-types (Sb) — the accumulation of central mass destabilizes x_1 orbit families and removes the bar!

J. Beckman: May not the break in the luminosity function for the H II regions in the objects whose LF is of Type II represent *not* the behavior of the molecular cloud mass distribution but the transition from ionization-bounded to density-bounded regions? This is supported by the fact that the Type I galaxies don't have LFs which reach the critical turnover luminosity. Your comments please.

A. Phillips: That's a very interesting idea. The Type II LFs in SBb rings zones do occur in the regions of highest H II region density, and so the ionizing flux could be very high relative to the amount of gas present. The gas content is the crucial issue, because we certainly see Hα and H II region surface densities just as high or higher in later-type galaxies with Type I LFs (which *do* appear to extend above the break luminosity). What must be explained is why the Type II LFs are so shallow below the turnover. Unless there is a very strong and systematic incompleteness in the counts at low luminosity, then we still have a clear difference in slope between the Type I and II LFs.

J.-R. Roy: How could we exclude or prove formation of low mass stars in central regions of barred galaxies devoid of H II regions?

A. Phillips: I don't know of a good way to do this. Localized CO emission could reveal that the material is present and so stars are likely to be forming, and I suppose that IR emission without any sort of emission lines might be a signature of low-mass-only star formation — but I doubt that other processes could be ruled out as the cause of such emission.