HOW DIFFERENT ARE NORMAL AND BARRED SPIRALS?

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Received ________________; accepted ________________
No significant color differences are found between normal and barred spirals over the range of Hubble stages a - ab - b - bc. Furthermore no significant difference is seen between the luminosity distributions of normal and barred galaxies over the same range of Hubble stages. However, SBc galaxies are found to be systematically fainter than Sc galaxies at 99% confidence. The observation that normal and barred spirals with Hubble stages a - ab - b - bc have indistinguishable intrinsic colors hints at the possibility that the bars in such spiral galaxies might be ephemeral structures. Finally, it is pointed out that lenticular galaxies of types S0 and SB0 are systematically fainter than are other early-type galaxies, suggesting that such galaxies are situated on evolutionary tracks that differs systematically from those of galaxies that lie along the E - Sa - Sb -Sc and E - SBa - SBb - SBc sequences.

Subject headings: galaxies: evolution, galaxies: photometry
1. INTRODUCTION

The present paper asks three questions that (as far as I have been able to determine) have not been asked before: (1) Do normal and barred of the same Hubble stage have different colors, (2) do normal and barred galaxies of the same Hubble stage have different luminosities and (3) is the frequency distribution of r (ring) and s (sprial) type substructures within galaxy disks different in normal and barred galaxies? It should be emphasized that the present selection of galaxies by morphological type is radically different from other recent investigations (e.g. Giordano et al. 2010, Masters et al. 2010, Nair & Abraham 2010) that select galaxies by color, or by luminosity and then compare the relative frequencies of normal and barred objects.

Surprisingly there appears to be no discussion in the astronomical literature of possible systematic differences between the colors and luminosities of normal and barred spiral galaxies that have been selected on the basis of their morphologies. Since the colors of galaxies are known to become bluer with advancing Hubble stage it is clear that any subtle color differences between normal and barred objects of a given Hubble stage, can only be studied effectively using galaxy classifications that are of the very highest quality. The gold standard of such classifications is provided by the 1246 galaxies in *A Revised Shapley-Ames Catalog of Bright Galaxies* by Sandage & Tammann (1981). These classifications, by two expert morphologists, are based exclusively on inspection of large-scale photographic plates that are all beautifully illustrated in *The Carnegie Atlas of Galaxies* (Sandage & Bedke 1994). The Shapley-Ames Catalog of Bright Galaxies constitutes a magnitude-limited sample, which is an enormous advantage for morphological studies. This is so because luminosity-limited samples are biased towards luminous galaxies, which exhibit striking morphological differences. This contrasts with the situation for volume-limited samples which are dominated by intrinsically faint galaxies for which morphological differences tend
to be much more subtle (van den Bergh 1998, p.25). A problem with luminosity-limited samples is, of course, that they may be biased by luminosity selection. However, as will be seen in Section 3 of the present paper, there appear to be no significant luminosity differences between normal and barred spirals over the range of Hubble stages a - ab - b - bc. Therefore the Shapley-Ames sample is ideally suited for a study of possible systematic differences between normal and barred galaxies.

Edwin Hubble (1926, 1936) suggested that spiral galaxies could be arranged into a ‘tuning fork’ diagram, in which the tines are represented by normal and barred objects. Later (e. g. van den Bergh 1998) it became clear that this dichotomy extends to the realm of the irregular galaxies with the SMC being an example of a normal irregular an the LMC being a barred irregular galaxy. Furthermore (see for example Sandage 1975) lenticular galaxies were also found to exhibit either normal (S0) or barred (SB0) morphology. Sandage (1975) and Sandage & Tammann (1981) assign the overwhelming majority of spiral galaxies to either the normal or barred type, with few intermediate objects. On the other hand de Vaucouleurs (1959) advocated a classification system in which bar strength varied continuously from pure spirals of type SA, through intermediate objects of type SAB, to pure bars assigned to type SB. Galaxies that Sandage & Tammann classified as being edge-on were excluded from the sample because it is often difficult (or impossible) to distinguish normal and barred spirals that are viewed edge-on. Also excluded were those galaxies which Sandage & Tammann classified as being ‘peculiar’. Some of such peculiar galaxies turned out to be unusually blue, indicating that their apparent peculiarity is due to (or associated with) a recent burst of star formation. The adopted luminosities of galaxies are the $M_{B_T}^{o,i}$ values of Sandage & Tammann (1981). In the subsequent discussion these magnitudes will, for the sake of simplicity, be referred to as $M_B$. For the majority of the galaxies in the Shapley-Ames catalog total (asymptotic) colors on the Johnson B-V system, that have been corrected for Galactic and internal extinction, and for the effects of
redshift, are available from the *Third Reference Catalogue of Bright Galaxies* (=RC3) by de Vaucouleurs et al. (1991). These intrinsic colors will subsequently be designated \((B - V)_o\).

2. COLORS OF NORMAL AND BARRED SPIRALS

The following discussion is based on all those galaxies in the Revised Shapley-Ames Catalog which are not classified as ‘edge-on’ or as ‘peculiar’, and for which the RC3 catalog gives \((B - V)_o\) colors. [For both normal spirals and for barred spirals the fraction of objects classified as being peculiar by Sandage & Tammann lies between 5% and 6%]. It is not clear that the observed distribution of \((B - V)_o\) colors for any Hubble type will be Gaussian. The following discussion is therefore based on the median colors \((B - V)_o^*\) of different subgroups, rather than on their mean values \(<(B - V)_o>\). A comparison between these median colors of normal spiral and of barred galaxies is shown in Table 1 and is plotted in Figure 1. Also listed in this table are the \((B - V)_o^*\) colors containing 25% and 75% of the data points and error estimates based on the inter-quartile range divided by the square root of the number of galaxies. Inspection of the data in Table 1 shows that, within any Hubble stage, the colors of normal and barred objects are very similar. This conclusion is strengthened and confirmed by Kolomogorov-Smirnov (K-S) tests which show no significant differences between the color distributions of Sa and SBa, Sab and SBab, Sb and SBb, Sbc and SBbc and Sc and SBc galaxies. The largest difference in Table 1 occurs between the colors of Sc and SBc galaxies, with the SBc galaxies appearing, on average, slightly bluer than those of type Sc. The observed color between Sc and SBc galaxies is in the sense expected from the fact (see Section 3) that SBc galaxies are systematically fainter (and hence are expected to be metal poorer) than are objects of type Sc. It is concluded that presently available high-quality data do not exhibit a significant difference between the intrinsic \((B - V)_o\) colors of normal and barred galaxies over the range of Hubble stages a
- ab - b - bc. The referee has raised the interesting question whether the presence of bars in galaxies might have affected the Hubble stage assignments of galaxies in the catalog of Sandage & Tammann (1981) in a systematic way. With the passing of Allan Sandage it appears unlikely that this question will ever be answered in an entirely satisfactory fashion.

3. LUMINOSITIES OF NORMAL AND BARRED SPIRALS

The Revised Shapley-Ames Catalog (Sandage & Tammann 1981) lists the $M_B$ luminosities for all of the galaxies in their sample. A summary of the data on the median luminosities of normal and barred galaxies is given in Table 2. Also given for comparison is the median luminosity of the elliptical galaxies listed in the Shapley-Ames catalog. These data can be used to search for systematic luminosity differences between normal and barred spirals. For each Hubble stage in the range a - ab - b - bc such a comparison shows no clear-cut difference between the luminosity distributions of normal and barred spirals. Since the mass-to-light ratios are expected to be similar within each Hubble stage this result suggests that normal and barred spirals of Hubble stages a - ab - b - bc have similar masses, i.e. the difference between barred and non-barred spirals is not a consequence of mass differences. However, a K-S test does show (at $> 99\%$ significance) that barred spiral of type SBc are systematically fainter than normal spirals of type Sc. For 264 Sc galaxies $M^*_B = -20.86$, compared to $M^*_B = -20.20$ for 69 SBc galaxies. Since faint galaxies of a given Hubble type are systematically slightly bluer than luminous galaxies of the same type one would expect the average colors of SBc galaxies to be slightly bluer than those of type Sc. This is, in fact, the sense of the color differences listed in Table 1. So metallicity effects may have provided a slight boost to the apparent systematic color difference between Sc and SBc galaxies. It is noted parenthetically that the luminosity distributions of S0 and SB0 galaxies in Sandage & Tammann (1981) do not differ significantly. The fact that the
numbers of galaxies in Table 2 is greater than that in Table 1 is due to the fact that all galaxies listed in the Shapley-Ames catalog have been assigned luminosities, whereas B-V colors from the RC3 are available for most, but not all, of the individual galaxies contained in that catalog.

The referee of this paper has expressed some concern about the fact that the luminosities of field galaxies in the Shapley-Ames catalog were determined from their radial velocities and might therefore be affected by the random motions of galaxies. It therefore seemed prudent to repeat the data on the median luminosities of galaxies listed in Table 2 using only (1) galaxies that are members of clusters identified by Sandage & Tammann (1981) and (2) field galaxies with radial velocities (corrected for motion relative to the centroid of the Local Group) $> 2000 \text{ kms}^{-1}$, for which radial velocities should provide a reasonable proxy for distances. The results for these galaxies for which the luminosities are most secure are listed in Table 3. These data confirm the previous conclusion that barred and unbarred galaxies of Hubble stages a - ab - b - bc have similar luminosities, and hence presumably comparable masses. As was the case in Table 2, galaxies of type SBc are again (on average) found to be less luminous than those of type Sc.

Finally a comparison between the luminosity distributions of various kinds of early-type galaxies is shown in Table 4 and is plotted in Figure 2. The most striking feature of these data is that the S0 + SB0 galaxies are, on average, about a magnitude fainter than are E and Sa + SBa galaxies. A K-S test shows that there is less than a 0.1% chance that the S0 + SB0 sample was drawn from the same parent population as that of the E and Sa + SBa galaxies. This result strongly suggests that S0 + SB0 galaxies lie on evolutionary tracks that, on average, differ significantly from those of galaxies that fall along the E - Sa - Sab - Sb - Sbc and E - SBa - SBab - SBb - SBbc sequences. The data presented above show, as has previously been emphasized by van den Bergh (1998, p.61), that S0 galaxies are
not truly intermediate between galaxies of types E and Sa. This view conflicts with that of Hubble (1936, pp.44-45) who introduced S0 galaxies as a “more or less hypothetical” class to bridge the chasm between elliptical and spiral galaxies. The data listed in Table 3 also show that the systematical luminosity difference between S0 galaxies on the one hand, and E and Sa galaxies on the other, is also present in the sub-sample of galaxies with the best-determined luminosities.

4. OTHER STRUCTURE WITHIN DISKS

Following in the footsteps of de Vaucouleurs (1959), Sandage & Tammann (1981) classified the structure within some disk galaxies as consisting of rings (r), intermediate types (rs) and spiral-like features (s). The r and s types of structures occur approximately with equal frequency in early-type (Sa and SBa) galaxies, whereas spiral-like features predominate in late-type spirals. Within each Hubble stage, and within the accuracy of the statistics derived from the data in A Revised Shapley-Ames Catalog of Bright Galaxies (excluding peculiar and edge-on galaxies), there appears to be no systematic differences between the luminosity distributions of parent galaxies having r, rs and s type structures. Furthermore, no significant differences are seen between the \((B - V)_o\) color distributions of spiral (r), intermediate (rs), and ringed (r) galaxies of a given Hubble stage. Finally, within the accuracy of the statistics provided by Sandage & Tammann (1981), there is no difference in the relative frequency of r and s type structures between galaxies with, and without, bars.
5. CONCLUSIONS

Surprisingly it has been found that, for galaxies of Hubble stages in the range a - ab - b - bc, normal and barred galaxies have indistinguishable $(B - V)_o$ color distributions. Furthermore, within any given Hubble stage, the intrinsic color distribution of galaxies is found to be insensitive to (or independent from) the presence of spiral-like or ring-like features. Taken at face value, the fact that intrinsic color of a galaxy does not depend on the presence (or absence) of a bar is surprising because one might have expected (see Kormendy & Kennicutt 2004 for a review) that the existence of a bar would rearrange disk gas resulting in transport of disk gas to small radii where it reaches high density and plausibly feeds into star formation. According to Combes (2008) gas is driven inwards by bar torques. The gas angular momentum is taken up by the bar which is sufficient to weaken or destroy it. The history of star formation determines the evolution a bar (Combes 2008) and hence the present intrinsic color of a galaxy. One might therefore have expected the presence (or absence) of a bar to have affected present galaxy colors. Perhaps the apparent independence of the intrinsic colors of spirals from the presence (or absence) of bars hints at the possibility that some bars could be ephemeral structures. Since it is not the central mass concentration which destroys the bar, it is relatively easy to reform a bar after a bar episode is completed. With significant cosmological gas accretion rates several bar episodes might occur in a galaxy with timescales of a few Gyr. On the other hand Sánchez-Blázquez et al. (2011) have argued that some bars formed long ago and have survived to the present day.

I am indebted to Ron Buta, John Kormendy and Preethi Nair for a number of exchanges of e-mail regarding the differences between normal and barred spiral galaxies. I also thank Jason Shrivell and Brenda Parrish for technical assistance and the referee for a number of helpful suggestions.
Table 1. Median Colors of Normal and Barred Spiral Galaxies

| Type    | \((B - V)_o\) | n  | 25%   | 75%   |
|---------|---------------|----|-------|-------|
| Sa      | 0.82 +/- 0.01 | 41 | 0.79  | 0.86  |
| SBa     | 0.84          | 24 | 0.81  | 0.92  |
| Sab     | 0.74          | 32 | 0.67  | 0.81  |
| SBab    | 0.77          | 5  | 0.67: | 0.87: |
| Sb      | 0.68          | 75 | 0.64  | 0.76  |
| SBb     | 0.68          | 30 | 0.54  | 0.72  |
| Sbc     | 0.60          | 54 | 0.55  | 0.67  |
| SBbc    | 0.62          | 38 | 0.57  | 0.67  |
| Sc      | 0.53          | 188| 0.44  | 0.57  |
| SBc     | 0.48          | 45 | 0.44  | 0.58  |

Uncertain values are marked by a colon
Table 2. Median Luminosities of Normal and Barred Galaxies

| Type | $M_B^*$  | n    | 25%  | 75%  |
|------|---------|------|------|------|
| E    | -21.32 +/- 0.11 | 144  | -21.85 | -20.58 |
| S0   | -20.44 0.12     | 99   | -21.11 | -19.96 |
| SB0  | -20.33 0.18     | 31   | -20.76 | -19.77 |
| Sa   | -21.04 0.13     | 68   | -21.53 | -20.49 |
| SBa  | -21.04 0.17     | 29   | -21.24 | -20.35 |
| Sab  | -21.10 0.20     | 36   | -21.95 | -20.73 |
| SBab | -22.22 0.27     | 9    | -22.57 | -21.75 |
| Sb   | -21.65 0.17     | 91   | -22.53 | -20.88 |
| SBb  | -21.81 0.18     | 37   | -22.35 | -21.27 |
| Sbc  | -21.30 0.13     | 68   | -21.83 | -20.75 |
| SBbc | -21.41 0.16     | 47   | -22.04 | -20.91 |
| Sc   | -20.86 0.09     | 264  | -21.56 | -20.99 |
| SBc  | -20.20 0.17     | 69   | -21.06 | -19.61 |
Table 3. Median luminosities of Normal and Barred Galaxies for objects located in clusters or with $V > 2000 \text{ kms}^{-1}$

| Type  | $M^*_B$   | n | 25%    | 75%    |
|-------|-----------|---|--------|--------|
| E     | -21.61 +/- 0.09 | 99 | -22.08 | -21.16 |
| S0    | -20.95 0.23  | 50 | -21.48 | -19.82 |
| SB0   | -20.30 0.38  | 17 | -21.33 | -19.77 |
| Sa    | -21.44 0.17  | 37 | -22.08 | -21.04 |
| SBa   | -21.18 0.12  | 12 | -21.33 | -20.90 |
| Sab   | -21.85 0.30  | 18 | -22.42 | -21.17 |
| SBab  | -21.96 0.25  | 6  | -22.57 | -21.96 |
| Sb    | -22.33 0.16  | 41 | -22.69 | -21.65 |
| SBb   | -21.92 0.15  | 25 | -22.48 | -21.74 |
| Sbc   | -21.79 0.17  | 34 | -22.33 | -21.31 |
| SBbc  | -21.71 0.17  | 26 | -22.23 | -21.37 |
| Sc    | -21.52 0.09  | 102| -21.93 | -20.98 |
| SBc   | -21.05 0.36  | 24 | -21.66 | -19.89 |
Table 4. Luminosity Distribution of Early-type Galaxies

| $M_B$       | E | S0+SB0 | Sa+Sba |
|-------------|---|--------|--------|
| -23.00 to -23.49 | 1 | 0      | 0      |
| -22.50 to -22.99 | 12| 1      | 2      |
| -22.00 to -22.49 | 13| 3      | 8      |
| -21.50 to -21.99 | 36| 11     | 13     |
| -21.00 to -21.49 | 29| 19     | 32     |
| -20.50 to -20.99 | 20| 21     | 14     |
| -20.00 to -20.49 | 11| 21     | 15     |
| -19.50 to -19.99 | 12| 30     | 10     |
| -19.00 to -19.49 | 4 | 16     | 2      |
| -18.50 to -18.99 | 3 | 4      | 1      |
| -18.00 to -18.49 | 1 | 3      | 0      |
| -17.50 to -17.99 | 0 | 0      | 0      |
| -17.00 to -17.49 | 1 | 1      | 0      |
| > -17.00       | 1 | 0      | 0      |
| Total          | 144| 130    | 97     |
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Fig. 1.— Intrinsic colors of normal spirals (red circles) and of barred spirals (blue dots) as a function of Hubble stage. The figure shows that the colors of barred and unbarred spirals are indistinguishable over the range of Hubble stages a - ab - b - bc.
Fig. 2.— Histogram of the luminosity distribution of elliptical (red), S0+SB0 (blue) and Sa+Sba galaxies (green) in the Shapley-Ames catalog. The figure shows that S0 galaxies are systematically fainter than either E or Sa galaxies. This suggests that lenticular galaxies