THE VISIBILITY OF GALACTIC BARS AND SPIRAL STRUCTURE AT HIGH REDSHIFTS

SIDNEY VAN DEN BERGH
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada; sidney.vandenbergh@nrc.ca

ROBERTO G. ABRAHAM
Department of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada; abraham@astro.utoronto.ca

LAURA F. WHYTE and MICHAEL R. MERRIFIELD
School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK; ppxfmw@unix.ccc.nottingham.ac.uk, michael.merrifield@nottingham.ac.uk

PAUL B. ESKRIDGE
Department of Physics and Astronomy, Minnesota State University, Mankato, MN 56001; paul.eskridge@mnsu.edu

AND

JAY A. FROGEL and RICHARD POGGE
Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210; frogel@astronomy.ohio-state.edu, pogge@astronomy.ohio-state.edu

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ABSTRACT

We investigate the visibility of galactic bars and spiral structure in the distant universe by artificially redshifting 101 $B$-band CCD images of local spiral galaxies from the Ohio State University Bright Spiral Galaxy Survey. These local galaxy images represent a much fairer statistical baseline than the galaxy atlas images presented by Frei et al. in 1995, the most commonly used calibration sample for morphological work at high redshifts. Our artificially redshifted images correspond to Hubble Space Telescope $I_{814}$-band observations of the local galaxy sample seen at $z = 0.7$, with integration times matching those of both the very deep northern Hubble Deep Field (HDF) data and the much shallower HDF flanking field observations. The expected visibility of galactic bars is probed in two ways: (1) using traditional visual classification and (2) by charting the changing shape of the galaxy distribution in “Hubble space,” a quantitative two-parameter description of galactic structure that maps closely onto Hubble’s original tuning fork. Both analyses suggest that over two-thirds of strongly barred luminous local spirals (i.e., objects classified as SB in the Third Reference Catalogue) would still be classified as strongly barred at $z = 0.7$ in the HDF data. Under the same conditions, most weakly barred spirals (classified SAB in the Third Reference Catalogue) would be classified as regular spirals. The corresponding visibility of spiral structure is assessed visually, by comparing luminosity classifications for the artificially redshifted sample with the corresponding luminosity classifications from the Revised Shapley-Ames Catalog. We find that for exposure times similar to that of the HDF, spiral structure should be detectable in most luminous ($M_B \sim M^*$) low-inclination spiral galaxies at $z = 0.7$ in which it is present. However, obvious spiral structure is only detectable in $\sim 30\%$ of comparable galaxies in the HDF flanking field data using the Wide Field Planetary Camera 2. Our study of artificially redshifted local galaxy images suggests that, when viewed at similar resolution, noise level, and redshift-corrected wavelength, barred spirals are less common at $z = 0.7$ than they are at $z = 0.0$, although more data are needed to definitively rule out the possibility that cosmic variance is responsible for much of this effect.

Key words: galaxies: evolution — galaxies: fundamental parameters

1. INTRODUCTION

The Hubble Space Telescope (HST) has, for the first time, allowed the direct study of galaxies as they appeared when the universe was much younger than it is at the present time. Inspection of the images of such distant galaxies shows that the Hubble tuning-fork diagram does not provide an adequate framework for the classification of distant galaxies (van den Bergh et al. 1996) and that the fraction of peculiar and merging galaxies increases with redshift (Abraham et al. 1996a, 1996b). Around one-third of luminous galaxies lie off Hubble’s tuning fork at $z = 1$ (Brinchmann et al. 1998). A number of studies have also claimed that the percentage of barred spirals seems to decrease toward larger look-back times (van den Bergh et al. 1996; Abraham et al. 1999). This trend has been based on the results from objective, but rather coarse-grained, automated morphological classifications. More fine-grained “precision morphology” (which can subdivide spiral galaxies into various classes, for example) still requires a trained human eye. On this basis, van den Bergh et al. (2000) and van den Bergh, Cohen, & Crabbe (2001) note that the fraction of “grand design” spirals appears to decrease rapidly with increasing redshift. It is important to emphasize that these studies focus mainly on galaxies at redshifts $z < 1$, so that systematic changes in galaxy appearance due to shifting of the filter bandpass in
the rest frame of the galaxy are easily understood. For example, at $z \sim 0.7$, HST imaging using the F814W filter corresponds quite closely to $B$-band imaging in the rest frame of the galaxy.

However, an alternative interpretation of the absence of barred and grand-design spirals at high redshifts is that the features that define these categories of objects locally are undetectable outside of the nearby universe. The visibility of these features at high redshifts has been poorly understood because of the absence of a suitable CCD-imaging sample of representative local galaxies. Such samples can be used to test the visibility of fine structures in galaxies by “artificial redshifting,” in which images are binned and noise is added in order to mimic the appearance of high-redshift counterparts. In the present paper, we will adopt this strategy using a new sample of local galaxy images taken from the Ohio State University Bright Spiral Galaxy Survey (Frogel, Quillen, & Pogge 1996). This sample provides a more statistically fair representation of the local morphological mix than other samples used to calibrate high-redshift morphology by artificial redshifting.

In this paper, we quantify the systematic effects of decreasing resolution (and of increasing noise) on the visibility of galactic bars and grand-design spiral structure using a mixture of techniques. Where possible, we will back up traditional visual classifications using quantitative measures. A useful tool in this regard is what Abraham & Merrifield (2000) have dubbed “Hubble space,” a quantitative two-parameter description of galactic structure that maps closely onto Hubble’s original tuning fork. When no suitable quantitative measure exists, as for describing the existence of grand-design spiral structure, we unapologetically adopt a purely visual approach.

A plan for this paper follows: In § 2, we describe our sample and highlight its advantages (and deficiencies) when it is used to calibrate morphology at intermediate redshifts of around $z = 0.7$. In § 3, we revisit the visual classifications for the galaxies in the sample and compare the classifications used in the present paper with those from existing catalogs. In § 4, we introduce the Hubble-space diagram for our sample. In § 5, we describe our artificially redshifted sample and analyze the robustness of various features in the galaxy images, using both visual classifications and quantitative measures. The visibility of grand-design spiral structure is analyzed in § 6. Our results are discussed in § 7 and our conclusions summarized in § 8. Finally, we note that throughout the present paper we adopt a cosmology in which $\Omega = 0.7$, $\Omega_M = 0.3$, and $\Omega_L = 0.7$.

2. THE OSU BRIGHT SPIRAL GALAXY SURVEY

Our data set consists of 101 $B$-band images of galaxies taken from the Ohio State University Bright Spiral Galaxy Survey (BSGS; Frogel et al. 1996; Eskridge et al. 2002). The BSGS is a survey consisting of $BVRJHK$ images for 205 objects selected from the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991). Our subsample of these data consists of all $B$-band images that were available at the time of writing. The BSGS is constructed from the RC3 on the basis of three simple criteria: (1) no E or S0 galaxies are included; (2) $B < 12$ mag; (3) galaxy diameter $\leq 6.5'$. The reader is referred to Frogel et al. (1996) for details. The diameter limit imposed on the sample was intended to ensure that all galaxies fit on the various detectors used and is relatively unimportant, as 95% of the $B < 12$ spiral galaxies in the RC3 are imaged in the BSGS.

It is important to consider whether any important biases are introduced by restricting our consideration to a subset of the full BSGS in this manner (we reemphasize that since the BSGS as a whole is 95% complete, the full survey has no important biases with respect to the RC3 selection criteria). In Figure 1, we present histograms showing the frequency of the barred and regular spirals in our sample of 101 galaxies from the BSGS as a function of Hubble stage and compare these with the corresponding histograms for the full RC3, cut at the same limiting magnitude as the BSGS. Note that in this figure (and throughout the remainder of this paper), we will adopt the terminology of the RC3, which corresponds quite closely to $z = 0.7$, as indeed are all magnitude-limited samples of bright galaxies. This is clear from Figure 2, which shows the $B$-band absolute magnitude distribution for galaxies in the BSGS along with a Schechter function empirically normalized to the bright shoulder of the distribution. As expected from a magnitude-limited sample, the absolute magnitude distribution for galaxies in BSGS is peaked at $M_B^*$ and drops off sharply at both the bright and faint ends. At $z = 0.7$, the F814W filter on HST is roughly synchronized to rest-frame $B$ band, so the effects of “morphological K-corrections” are small and $B$-band local images are well matched to $I_{814}$-band $HST$ data. Therefore, in Figure 2 we also show dashed lines that indicate the absolute magnitude limits corresponding to $I_{814} = 22$, the magnitude limit adopted for morphological classification in the Medium Deep Survey (Griffiths et al. 1994; Glazebrook et al. 1995; Abraham et al. 1996a, 1996b), and $I_{814} = 23.2$, the magnitude limit corresponding to the

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1 Note that in the standard encoding from the RC3 given the second column of Table 1, SAB spirals are encoded as type SX.
bar visibility study of Abraham et al. (1999). On the basis of this figure, it is clear that (1) the BSGS is reasonably well matched to shallow (several-orbit) HST imaging observations, such as those of the Medium Deep Survey, the Hawaii Deep Survey, and the CFRS/LDSS imaging surveys, but (2) deep HST observations, such as those in the Hubble Deep Fields, will probe much further down the luminosity function than the galaxies represented in the BSGS. This is true even in the no-evolution case, but ultimately how far down the luminosity function we look depends critically on the amount of luminosity evolution. With strong evolution we can of course probe distant galaxies that would have been quite faint in the absence of luminosity evolution. The implications of this will be considered in § 7.

3. VISUAL CLASSIFICATIONS

In order to allow a consistent comparison between the artificially redshifted morphologies of the galaxies in our sample and their local morphologies, one of us (S. v. d. B.) visually reclassified the local galaxy sample using the DDO system of van den Bergh (1960a, 1960b, 1960c). Results from this procedure are shown in Table 1 (along with the
| ID     | RC3   | RSA   | $z = 0.0^c$ | $z = 0.7$ HDF$^a$ | $z = 0.7$ FF$^c$ | $M_{NGC}^{+0.7d}$ | $1 - (b/a)^e$ | Comment |
|--------|-------|-------|-------------|------------------|------------------|------------------|--------------|---------|
| NGC 150 | SBT3* | Sbc p II | Sbc I [2] | Sc [2] | ... | 22.29 | 0.47 |         |
| NGC 157 | SXT4 | Sc II–III | Sc I–II [2] | Sc I [2] | ... | 20.85 | 0.25 |         |
| NGC 210 | SXS3 | Sh I | Sh I [2] | S(B)bc II I [2] | Sb [0] | 21.58 | 0.12 | Lens |
| NGC 278 | SXT3 | Sbc II | Sbc [2] | Sa [0] | ... | 23.53 | 0.06 |         |
| NGC 289 | SBT4 | SBbc I–II | S(B)bc I [2] | S(B)bc II [2] | Sb [0] | 21.72 | 0.44 |         |
| NGC 428 | SXS9 | Sc III | SbcIII [2] | Sb p [2] | ... | 22.89 | 0.09 |         |
| NGC 488 | SAR3 | Sab I | Sa II [2] | Sa [2] | ... | 20.51 | 0.26 |         |
| NGC 578 | SXT5 | Sc I–II | Sbc I–II [2] | Sbc II [2] | Sbc [1] | 21.53 | 0.47 |         |
| NGC 613 | SBT4 | SBb II | S(B)bc I [2] | S(B)bc II [2] | SBB II [2] | 20.90 | 0.44 |         |
| NGC 625 | SBR9 | S p | Amorph. [0] | Sab [0] | ... | 24.89 | 0.47 | Dusty |
| NGC 685 | SXR3 | SBb II | S(B)bc III [2] | S(B)bc [2] | Sc I [2] | 21.92 | 0.19 |         |
| NGC 779 | SXR3 | Sh I–II | Sab II [2] | Sb [0] | ... | 22.22 | 0.66 |         |
| NGC 908 | SAS5 | Sc I–II | Sc I–II [2] | Sc II [2] | Sc II [2] | 20.70 | 0.57 |         |
| NGC 1042 | SXT6 | Sc I–II | Sc II [2] | Sc II [2] | Sc I [1] | 21.90 | 0.19 |         |
| NGC 1058 | SAT5 | Sc II–III | Sc [2] | Sa [0] | ... | 24.60 | 0.03 |         |
| NGC 1073 | SBT5 | SCbc II | SBBc II [2] | SBBc I [2] | ... | 22.19 | 0.07 |         |
| NGC 1084 | SAS5 | Sc I | Sc I [2] | Sc I [2] | Sc I [1] | 21.57 | 0.42 |         |
| NGC 1087 | SXST | Sc III–IV | Sc p[2] | Sbc p [2] | Sbc [0] | 21.62 | 0.40 |         |
| NGC 1187 | SBR5 | Sbc II | Sbc I–II [2] | SBC bc II–III [2] | Sbc II [2] | 22.90 | 0.09 |         |
| NGC 1511 | SA | Sc p | S[2] | Sb [1] | ... | 23.39 | 0.60 | Dusty, edge-on |
| NGC 1559 | SBS6 | SBbc II | S(B)bc I [2] | Sbc [2] | Sc [2] | 23.17 | 0.43 |         |
| NGC 1617 | SAS1 | Sbc II | Sbc II [2] | Sbc [0] | ... | 22.44 | 0.51 |         |
| NGC 1637 | SXT5 | SBbc II–III | Sbc II [2] | Sbc [1] | ... | 23.27 | 0.21 | Asymmetric |
| NGC 1703 | SBR3 | ... Sc I–II [2] | Sbc [1] | ... | 22.11 | 0.13 |         |
| NGC 1792 | SAT4 | Sc II | Sc [2] | Sc [2] | Sc [0] | 21.49 | 0.52 |         |
| NGC 1808 | RXS1 | Sa | Sab [2] | Sa [0] | Sc [0] | 21.82 | 0.59 |         |
| NGC 1832 | SR4 | Sbc | Sbc [2] | Sc [0] | ... | 21.71 | 0.31 | Barlike knots |
| NGC 2090 | SAT5 | Sbc | Sbc II [2] | Sbc [0] | ... | 23.34 | 0.57 |         |
| NGC 2139 | SXT6 | Sbc | S(B)bc II [2] | Sc t : [2] | S(B)bc [1] | 21.72 | 0.07 |         |
| NGC 2196 | SAS1 | Sbc | Sbc II [2] | Sbc [2] | Sbc [0] | ... | 21.04 | 0.17 |         |
| NGC 2442 | SXSA | SBbc II | SBBc I–II [2] | Sbb p [2] | SBBc II [2] | 21.62 | 0.33 |         |
| NGC 2775 | SAR2 | Sa | Sa [2] | Sab [0] | Sab [0] | 21.45 | 0.18 |         |
| NGC 3166 | SXT0 | Sa | Sab [2] | Sab [0] | Sa [0] | 21.77 | 0.55 |         |
| NGC 3169 | SAS1 | Sbc I–II | Sbc p[3] [2] | Sbp[2] | Sb p [0] | 21.66 | 0.40 | Dusty |
| NGC 3232 | SAS3 | Sbc | Sbc I–II [2] | Sbc [2] | Sbc [2] | 20.57 | 0.31 |         |
| NGC 3275 | SBR2 | SBab I | SBbc II [2] | Sbc [2] | Sbc [2] | 20.35 | 0.09 |         |
| NGC 3338 | SAS5 | Sbc I–III | Sbc I [2] | Sbc I [2] | Sbc I [2] | 22.27 | 0.59 | Asymmetric |
| NGC 3423 | SAS6 | Sc II | Sc II [2] | Sc [2] | ... | 23.03 | 0.19 |         |
| NGC 3511 | SAS5 | Sc III | Sc [2] | Sc [2] | ... | 22.31 | 0.66 | Dusty |
| NGC 3513 | SBT5 | SBbc II | SBbc II–III [2] | Sbc [2] | ... | 22.62 | 0.21 |         |
| NGC 3583 | SAS1 | Sbc | Sbc II [2] | Sbc p [2] | Sbc p [1] | 21.57 | 0.39 |         |
| NGC 3593 | SAS0 | Sa p | Sb III [0] | Sa [0] | ... | 24.12 | 0.51 | Edge-on |
| NGC 3646 | RING | Sbc p II | Sc p II [2] | Sc p I [2] | Sc p I [2] | 20.00 | 0.30 |         |
| NGC 3675 | SAS3 | Sh II | Sh II [2] | Sab [1] | ... | 22.76 | 0.51 |         |
| NGC 3681 | SXR4 | SBbc I–II | S(B)bc II [2] | Sbc [0] | ... | 22.37 | 0.06 |         |
| NGC 3726 | SXR5 | Sc II | Sc II [2] | Sc [1] | ... | 22.08 | 0.38 |         |
| NGC 3810 | SAT5 | Sc II | Sc I–II [2] | Sbc II [2] | Sbc II [2] | 22.42 | 0.30 |         |
| NGC 3877 | SAS5 | Sc II | Sc III [2] | Sc [0] | ... | 23.24 | 0.78 | Edge-on |
| NGC 3887 | SAS0 | Sa | Sbc [2] | Sbc [1] | S(B)bc : [0] | 21.55 | 0.65 | Lens? |
| NGC 3893 | SXT5 | Sc I | Sbc II [2] | Sbc [2] | ... | 22.05 | 0.31 |         |
| NGC 4027 | SBS8 | Sc II | S(B)bc p[2] | Sbc p [2] | Sbc p [2] | 21.69 | 0.27 | Tidal arm? |
| NGC 4030 | SAS4 | ... | Sbc I–II [2] | Sbc [2] | Sb [0] | 21.68 | 0.23 |         |
| NGC 4136 | SXR5 | Sc I–II | Sbc II–III [2] | Sbc II [2] | Sbc II [2] | 19.48 | 0.26 |         |
| NGC 4254 | SAS4 | ... | Sbc I–II | Sbc I–II [2] | Sbc I–II [2] | 22.78 | 0.47 | Edge-on |
| NGC 4314 | SBT1 | SBa | SBa p [2] | S(B)bc p [1] | ... | 22.78 | 0.47 |         |
We note that the fraction of barred galaxies in the RC3 is in good agreement with the corresponding value determined independently for the BSGS by Eskridge et al. (2000).

Gratifyingly good agreement is also found between the present luminosity classifications of galaxies and those by Sandage & Tammann (1981). These are also listed in Table 1. (Note that the quoted Carnegie classifications are simplifica-

classifications obtained from repeating this exercise with artificially redshifted and noise-degraded galaxy images, the results from which will be described in § 5). Hubble types are available for 91 of the galaxies in our sample from the Carnegie Atlas of Galaxies (Sandage & Bedke 1994). A comparison between our classifications and those in the Carnegie Atlas shows excellent agreement. The standard deviation of the differences between the Hubble types in these two data sets (after uncertain classifications, marked in Table 1 by a colon, have been excluded) is 0.41 Hubble classes. The mean difference between Hubble classification types for these two sets of data is found to be 0.00 ± 0.04 Hubble classes. The overall fraction of barred galaxies in each sample is also in good agreement, as shown in Table 2.2

2 Note that Sandage does not use de Vaucouleurs's notation SAB for weak bars but uses the designation S/SB for objects of intermediate type. In Table 2, the amalgamation of S. v. d. B. types S(B) and SB should be compared with Sandage's numbers for type SB.

TABLE 2

Frequency Distribution of Barred Spirals from Visual Classification

| Type           | Carnegie | $z = 0$ | $z = 0.7$ HDF | $z = 0.7$ FF |
|----------------|----------|---------|---------------|--------------|
| S             | 49 (71%) | 70 (70%)| 82 (81%)      | 47 (81%)     |
| S(B)          | 1 (1%)   | 17 (17%)| 12 (12%)      | 6 (10%)      |
| SB            | 26 (26%) | 11.5 (11%)| 7 (7%)        | 5 (9%)       |
| S(B) + SB     | 26 (26%) | 28.5 (28%)| 19 (19%)      | 11 (19%)     |

2 Sandage & Tammann 1981 do not use de Vaucouleurs type S(B).
fied: outer rings are not marked, ring [r] and spiral [s] subclasses are omitted, and luminosity classes are simplified, i.e., Sandage & Tammann’s class I.7 is quoted as I–II). After excluding objects with uncertain classifications, 43 pairs of luminosity classifications were available. The standard deviation of the difference between these classifications was found to be 0.66 luminosity classes. The mean difference, in the sense S. v. d. B. minus Carnegie, is +0.10 ± 0.05 luminosity classes, indicating that the Sandage & Tammann (1981) luminosity classes are very close to the DDO system of van den Bergh (1960a, 1960b, 1960c).

4. CORRELATIONS IN LOCAL HUBBLE SPACE

Using the sample of Frei et al. (1996), Abraham & Merrifield (2000) defined a quantitative two-dimensional morphological parameterization (“Hubble space”) whose x-coordinate measures central concentration of light and whose y-coordinate measures the degree to which a galaxy is barred in a quantitative way. A remarkably large amount of information concerning the properties of local galaxies can be inferred from a close inspection of Hubble space (Whyte et al. 2002), but for our present purposes, its most important characteristic is that it provides a convenient benchmark allowing us to understand how the systematics of galaxy morphology vary as a function of resolution and signal-to-noise ratio. In this section, we will describe the basic features of the local galaxy distribution in Hubble space, before moving on to describe how these properties change when our galaxy sample is artificially redshifted to \( z = 0.7 \).

The distribution of the present BSGS sample in Hubble space is shown in Figure 3. In the top left panel, colored symbols keyed to the scheme used in Figure 1 are used to

![Figure 3](image-url)

**Fig. 3.**—Distribution of our sample in the two-dimensional morphological parameter space defined in Abraham & Merrifield (2000). Top left: Colored symbols subdivide the galaxy population into morphological “form families,” based on classifications from the RC3. Unbarred (SA) spirals are shown in red, weakly barred spirals (SAB) are shown in green, and strongly barred (SB) spirals are shown in blue. The dashed line subdivides barred from unbarred galaxies rather cleanly. Unlike the corresponding figure for the Frei et al. (1996) sample (Abraham & Merrifield 2000), no obvious “tuning fork” shape (or even bimodality) emerges from this diagram. At best a hint of bimodality emerges when the diagram is restricted to symmetric galaxies, as described in the text. However, as was found in the analysis of the Frei et al. sample, weakly barred spirals are predominantly late-type (i.e., low central concentration). Top right: As for the previous panel, except with symbols keyed to Hubble stage via RC3 T-types. (At the extremes of the distribution, \( T = 0 \) corresponds to S0/a, and \( T = 9 \) corresponds to Sm. The full mapping between Hubble stage and T-type is shown at the top of Fig. 1.) Note the evident gradient in Hubble stage with central concentration. Bottom left: As for the previous panel, except with plot symbols keyed to rotational asymmetry, as defined by Abraham et al. (1996a, 1996b). Note how SB galaxies appear to be made up of two populations: a tight sequence of low-asymmetry galaxies, and an outlier population of highly asymmetric galaxies. Bottom right: As for the previous panel, except with plot symbols keyed to luminosity class from the Revised Shapley-Ames Catalog. For convenience, luminosity classes have been mapped onto a numerical sequence (e.g., type I = 1.0, II–III = 2.5). Galaxies with no luminosity classifications have been designated as class 0 and are shown as small black open circles.
subdivide the galaxy population into bar types, based on classifications from the RC3. The dashed line shown in the figure subdivides barred from unbarred galaxies extremely cleanly. As was found for the Frei et al. (1996) sample analyzed in Abraham & Merrifield (2000), there is essentially no intermixing of unbarred galaxies and strongly barred galaxies in Hubble space, and weakly barred spirals are seen to be predominantly late-type (i.e., low central concentration). However, unlike the corresponding figure for the Frei et al. sample, no obvious “‘tuning fork’” shape (or even bimodality) emerges from this diagram.

In the top right panel of Figure 3, we show the same galaxy distribution in Hubble space, except with the symbols keyed to Hubble stage. This panel shows the obvious gradient in Hubble stage as a function of central concentration rather strikingly. This illustrates why Hubble space is a successful representation of the local galaxy data—measures of central concentration are clearly rather closely linked to Hubble stage. However, this panel provides a warning against basing morphological classifications of distant galaxy images solely on perceived central concentration or bulge-to-disk ratio (Abraham 1999). The mixed criteria (bulge-to-disk ratio, tightness of spiral structure, and degree of resolution in the arms) used to define visual classifications on the classical tuning fork make distinguishing between various types later than $T = 5$ impossible on the basis of central concentration of light. This is in accord with the general “‘rule of thumb” that central concentration is only used as a classification criterion for objects of early and intermediate type. Late types are generally seen with open enough arms that an adequate classification can be made without invoking any visual bulge-to-disk ratio criterion.

The distribution of galaxies in Hubble space keyed to rotational asymmetry (determined using the method given in Abraham et al. 1996a, 1996b) is shown in the bottom left panel of Figure 3. It is interesting that SB galaxies appear to be made up of two populations: a tight sequence of symmetric objects and an outlier population of highly asymmetric galaxies. Furthermore, a hint of bimodality (whose reality will be interesting to test once the full BSGS data become available) appears in the plot when consideration is restricted to galaxies with a high degree of symmetry. Our tentative explanation for the tuning-fork shape seen in the Hubble-space distributions of Abraham & Merrifield (2000) is that the galaxies in the Frei et al. (1996) sample were chosen to be visually “‘pretty,” and it seems this may be correlated with low asymmetry. In this connection, it is interesting to compare measurements of rotational asymmetry with more traditional visual methods for characterizing textural aspects of galaxy structure. In the bottom right panel of Figure 3, we show BSGS Hubble-space distribution keyed to luminosity classification. For convenience, luminosity classes have been mapped onto a numerical sequence (e.g., type I = 1.0, II–III = 2.5). Galaxies with no luminosity classifications are shown as small black open circles.

Most spirals in our sample are of luminosity class II. Because rotational asymmetry is measured by summing pixel-by-pixel differences, “ragged” spiral structure might be expected to slightly increase measured rotational asymmetry, although the effect is probably very small. In this connection, it is interesting to compare measures of asymmetry and luminosity classification. A comparison between the bottom two panels shows that luminosity and asymmetry are only very loosely correlated. Note however that luminosity classifications can only be applied to a subset of all systems in our sample. This is mainly because luminosity classifications are not defined for early-type spirals, because the spiral features in these objects are too short. Another factor is more subtle. For luminosity classes I–III, most of the weight in the classification comes from the strength and structure of the spiral arms. However, in classes III–V most of the weight comes from surface brightness, with the dwarfs having the lowest surface brightness. On Palomar Sky Survey plates all images have similar exposure times, so the apparent surface brightness is related to the intrinsic surface brightness and consistent luminosity classifications may be assigned to bulk samples of galaxies. However, this is not the case for the present images. As a result it is, on the basis of our present images, very difficult to assign luminosity classes to spirals of classes III–V. In practice this is not much of a problem, because most spirals in the our sample are intrinsically luminous.

5. ARTIFICIALLY REDSHIFTED IMAGES

Simulated $z = 0.7 I_{814}$-band HST images (corresponding to rest-frame $B$ band) for the 101 galaxies in our sample were constructed using the techniques described in Abraham et al. (1996a, 1996b; similar techniques are described by Giavalisco et al. 1996 and Takamiya 1999). Two sets of synthetic images were constructed, mimicking the exposure time and sampling of the $I_{814}$-band image of the northern Hubble Deep Field (123,600 s exposure with $0.04$ pixel$^{-1})$ and of a typical flanking field image (4000 s exposure, $0.1$ pixel$^{-1})$. Parameters defining Hubble space were remeasured from these degraded frames, which were also visually classified onto the DDO system by S. v. d. B. The images were given a final visual inspection by one of us (R. G. A.), who assigned a simple numerical index to each image denoting the visibility of spiral structure, as described in § 6. For the synthetic Hubble Deep Field images, visual inspections were limited to $I_{814} < 25$ mag, corresponding to the magnitude limit typically used by investigators working on galaxy morphology in the HDF. Similarly, visual inspection of the synthetic flanking field (FF) data was limited to $I_{814} < 22$. A summary of our results for the simulated HDF and FF data is included in Table 1. Classifications in the simulated FF images have been limited to $I < 22$ (corresponding to the typical magnitude limit from the Medium Deep Survey data).

5.1. Robustness of Visual Classifications

Results from the visual classification of the present sample are tabulated in Table 2, which shows a comparison between our local bar-strength classifications and those at $z = 0.7$ for both the HDF and the FF signal-to-noise ratio. The table shows the following: (1) The fraction of SB + S(B) galaxies is 28% for both the Sandage & Tammann (1981) classifications in the Carnegie Atlas and in S. v. d. B.’s classifications of the BSGS galaxies at $z = 0.0$. If the resolution of images is degraded to that of HDF galaxies at $z = 0.7$, then the fraction of SB + S(B) galaxies that can still be recognized as such drops from 28% to 19%. (3) At first sight, it might be unexpected that the fraction of SB + S(B) galaxies that can still be recognized as such remains constant at 19% when the signal-to-noise ratio is decreased to that in the flanking fields. The reason for this is...
probably that the FF galaxies, which all have $I_{<14} < 22.0$, are brighter than the HDF galaxies, for which $I_{<14} < 23.2$. In summary, the main result obtained from Table 2 is that roughly two-thirds of strongly barred galaxies will still be recognizable as such at $z = 0.7$. For weakly barred galaxies, the fraction of recognizable bars drops from 17% at $z = 0.0$ to $\sim 12\%$ at $z = 0.7$ for the HDF signal-to-noise ratio and $\sim 10\%$ for that of the flanking fields.

Among the 101 local spiral galaxies with images degraded to $z = 0.7$ that are listed in Table 1, 81 are of type S, 12 are of type S(B), S(B:), or S(B?), and eight are of type SB. For comparison, van den Bergh et al. (2000) found only S galaxies and no objects of type S(B) or SB among 18 comparable HDF spirals with $0.55 < z < 0.85$. Taken at face value, this result appears to confirm the conclusion by van den Bergh et al. (1996) that barred spirals are deficient at large redshifts. Among the local spirals listed in Table 2, a total of 63 have $I < 22$ and may therefore be compared with those in the flanking fields for which van den Bergh et al. (2000) have given classifications. Of the galaxies in Table 2 that have $I < 22$, 51 are found to be of type S, seven of type S(B), and five of type SB. For comparison, the numbers of comparable spirals in the flanking fields with $0.55 < z < 0.85$ are found to be 42 of type S, two of type S(B), and none of type SB. It is concluded that at comparable resolution and noise, the fraction of barred spirals in the flanking fields ($2/44 = 5\%$) appears to be lower than it is among nearby galaxies ($12/63 = 19\%$).

A graphical summary of the results presented in this section is shown in Figure 4. This figure also sheds some light on the statistical significance of claims for an absence of bars in the HDF observations. The relative bar fractions determined from the artificially redshifted and observed samples suggest that the absence of high-redshift bars is formally at least a $2\sigma$ effect. However, as described in § 7, it is wise to remain cautious given the small volume of the Hubble Deep Fields and the possibility of environmental effects that might skew the relative abundance of barred spirals as a function of environment.

Before leaving visual classifications (which we will return to in § 6) to consider their automated counterparts in the next section, it is worth emphasizing a final point: when spiral structure is not visible in a high-redshift galaxy, the system is not usually classified as a peculiar galaxy on this basis by experienced morphologists (although a local disk galaxy without spiral arms would probably be classed as peculiar, or at least anemic). This is because spiral structure washes away at low signal-to-noise levels, while the nuclear bulge and disk do not. Therefore, such systems are still classified as spiral galaxies (despite the absence of spiral structure) whose Hubble stage is determined solely on the basis of apparent bulge-to-disk ratio. The ramifications of this for both visual and automated classification are described in Abraham (1999). It is also worth emphasizing that in classification of galaxies on deep HST data, such as the HDF, S. v. d. B. denotes objects as “peculiar” only when they are not recognizable as disk or spheroid systems at all (e.g., when they have multiple nuclei and gross distortions). In most cases, a recognizable disk exhibiting peculiarity does so at a level where the distortion is best viewed as a perturbation superposed on a well-known galaxy form. Such systems are subclassed as peculiar, not superclassed as peculiar. For example, an early-type disk galaxy with a warp might be classed “Sa (pec),” but not as “pec.” The distinction between an object subclassed as peculiar and an object so peculiar that no association with a disk or spheroid is possible, is somewhat subjective at present. It would be worthwhile for this distinction to be placed on a more rigorous footing using objective or quantitative classifications in the future.

5.2. Robustness of Hubble Space

The sensitivity of the Hubble-space distribution to increasing noise and decreasing resolution is shown in Figure 5. The top row of this figure illustrates local Hubble space with plot symbols keyed to the bar classifications from the RC3 (left), the Revised Shapley-Ames Catalog (RSA; middle), and visual inspection by S. v. d. B. (right). A comparison of the local bar classifications reveals a number of interesting trends. First, as noted above, a simple cut in this parameter space isolates barred from unbarred spirals as classified in the RC3. A comparison between the RC3 and RSA panels shows a generally excellent agreement between the catalogs in the number of strongly barred spirals. An independent visual inspection by Eskridge et al. (2000) also results in close agreement with the numbers in the RC3. Note however the lack of systems classed as weakly barred in the RSA—weakly barred systems in the RC3 are generally classed as unbarred in the RSA, although virtually all such objects lie above the dashed line in the diagram (our proposed quantitative discriminator between barred and unbarred galaxies). This is a rather pleasing graphical demonstration of the fairly well known fact (Binney & Merrifield 1998) that the proportion of barred spirals in local catalogs varies between $\sim 30\%$ and $\sim 60\%$, and it highlights the subjective nature of assigning concrete classifications to systems in which a continuum of properties exists.

Even more striking evidence of this is the rightmost panel, which shows that S. v. d. B.’s criteria for classification as an SB galaxy are much stricter than those of the RSA. As described in the previous section, and as shown in Table 2, many systems classified as SB in the RC3 and RSA are classified as weakly barred S(B) galaxies by S. v. d. B.
The middle row of Figure 5 shows the Hubble-space distribution for galaxies degraded to the conditions in the northern HDF, with plot symbols color-coded according to their original classifications in the local images (i.e., to the classifications shown in the top set of panels). Over 90% of galaxies originally classified as SB remain above the dashed line, and these galaxies would thus also be classified as strongly barred in the HDF using the methodology of Abraham et al. (1999). While almost none of the spirals classified as S(B) by S. v. d. B. would be misclassified as regular spirals in the HDF, around half of the weakly barred (SAB) systems from the RC3 have migrated to the unbarred portion of the Hubble-space diagram. These weakly barred objects would have been classified as unbarred by the Abraham et al. (1999) HDF study. We conclude that, on the whole, the bars in strongly barred spirals (i.e., those systems classified SB in the RSA and RC3, and as SB or S(B) by S. v. d. B. in the present study) would remain visible in galaxies at $z = 0.7$ observed under the conditions of the central HDF.

The situation for shallower observations is less sanguine. The bottom row of Figure 5 shows the Hubble-space distribution for $I_{814} < 22$ mag galaxies degraded to the signal-to-noise ratio and resolution of the HDF flanking field observations. It is clear that in data of this quality (i.e., two-orbit exposures), only around 40% of strongly barred local spirals (at $I_{814} < 22$) would be classified as strongly barred at $z = 0.7$, in good agreement with the results obtained by visual inspection summarized in Table 2.

6. LUMINOSITY CLASSIFICATION AND GRAND-DESIGN SPIRALS

Luminosity classification of spiral galaxies (van den Bergh 1960a, 1960b, 1960c) is intrinsically more challenging than the assignment of Hubble types. Because the fine details of spiral structure are both smaller and of lower surface brightness than bars, assignment of luminosity classes is also more difficult than bar-strength classification. One would expect that only the strongest and most extended spiral features will remain visible in degraded images, that is, only “grand design” spirals are expected to be recognizable on noisy degraded images. Inspection of Table 1 shows that...
27 local spirals have both luminosity classifications by Sandage and luminosity classifications by S. v. d. B. in images degraded to HDF quality. It is encouraging to see that these two sets of luminosity classifications exhibit no statistically significant systematic difference: the standard deviation of the differences between the Sandage and S. v. d. B. classifications is found to be only 0.6 luminosity classes. Not unexpectedly, the fraction (9/26 = 35%) of spirals to which uncertain (marked with colons) luminosity classifications were assigned is greater for the high-noise images in Table 2 than it is the fraction of uncertain luminosity classifications (3/27 = 11%) for the lower noise images listed in Table 1. Since only three HDF spirals are known to have $0.60 < z < 0.80$ (see Table 2 of van den Bergh et al. 2000), it is not yet possible to establish whether the fraction of grand-design spirals is lower in situ at $z \sim 0.7$ than it is for the present sample of local spirals with images degraded to the appearance that they would have at $z = 0.70$.

Since, as described earlier, luminosity classes cannot be assigned to all spiral galaxies in which spiral structure is visible (e.g., early-type spirals), and since arms may still be visible in galaxies with insufficient signal to allow a reliable luminosity classification, it is interesting to consider what fraction of galaxies at $z = 0.7$ would show spiral features of any sort. In an attempt to determine this, one of us (R. G. A.) visually inspected the complete set of local and degraded images and assigned each galaxy a numerical index (0 = spiral structure invisible, 1 = hint of weak structure, 2 = obvious spiral structure) corresponding to qualitative visibility of spiral features. These numbers are included in Table 1, and Hubble-space plots summarizing the change in the visibility of spiral structure with redshift and noise are shown in Figure 6. In our local sample, 97% of galaxies showed “obvious” spiral structure. Under the conditions of the central HDF observations, obvious spiral structure is still seen in most (61%) galaxies at $z = 0.7$, with 82% showing at least a hint of structure. However, in the conditions corresponding to the HDF flanking field observations, only a minority (33%) of spiral galaxies now show obvious spiral structure, with 55% showing at least a hint of structure. Once again, we conclude that the deep central

![Image of spiral structure visibility plots](image)

**Fig. 6.**—Montage illustrating the degradation of spiral structure visibility with redshift and noise. **Top left**: Local luminosity classifications. Objects with no luminosity classifications are shown as small open circles. **Top right**: Visually assessed visibility of spiral structure keyed to symbol color. Galaxies with obvious spiral structure are shown in blue, galaxies with a hint of spiral structure are shown in green, and galaxies no visible spiral structure are shown in red. As described in the text, many objects for which no local luminosity classification is possible still show obvious spiral structure. Most of these galaxies are early-type systems (high central concentration). **Bottom left**: The corresponding plot for galaxies at a synthetic redshift of $z = 0.7$ as seen under the conditions of the central HDF field. Colors are keyed to classifications made directly from the synthetic high-redshift galaxies. Obvious spiral structure is still seen in most galaxies. **Bottom right**: As for the previous plot, except for conditions corresponding to the HDF flanking field observations. Galaxies showing obvious spiral structure are now a minority.
HDF observations allow quite robust conclusions to be drawn regarding galaxy morphology at $z = 0.7$, but that detailed morphological classifications (i.e., those more detailed than crude Hubble types) in the flanking fields should be treated with caution.

7. DISCUSSION

It is now commonly accepted that a large fraction of the galaxy population seen at large redshifts does not appear to fit comfortably within the tuning-fork classification scheme that provides a satisfactory framework for the classification of low-redshift galaxies in the $B$ band. While it seems likely that many of these peculiar galaxies are not isolated disk systems, the present paper does shed some light on the subset of high-redshift spirals classified as peculiar. (Since the BSGS sample is selected from galaxies with Hubble stages in the range $0 \leq T \leq 9$, it does not include systems classed as irregular or unclassifiable, and therefore the BSGS is not suitable for quantifying the proportion of nonspiral peculiar galaxies in deep images). Among the 101 BSGS galaxies, which are located at $z \sim 0.0, 12 (12\%)$ are classified as being peculiar on images degraded to $z = 0.7$ with HDF resolution and signal-to-noise ratio. For comparison, the data by van den Bergh et al. (2000) for HDF + FF spiral/disk galaxies at $0.60 < z < 0.89$ show that 17 out of 37 (46%) are classified as peculiar. In other words, approximately half of all spiral galaxies at look-back times of $\sim 8$ Gyr do not fit well into the Hubble classification system. Furthermore, van den Bergh et al. (2000) show that early-type galaxies are less likely to be peculiar than is the case for objects of later type. Only 1/22 (5%) of E–Sa–Sb galaxies are classified as peculiar, whereas 11/16 (69%) of Sb–Sbc galaxies are so classified. The majority of “Sc” galaxies at $z \sim 0.7$ are so peculiar that many of them have probably been called proto-Sc, pec, or “T”. In other words, it looks as though most compact early-type galaxies started to approach their “normal” present-day morphology faster than was the case for more extended objects of later morphological types. A caveat is however that it might be more difficult to recognize peculiarities in compact images of early-type galaxies than it would be to see such anomalies in the more open structure of late-type galaxies.

Our numerical experiments have given us some insight into the proportion of normal spirals that might be misclassified as peculiar because of noise and sampling. However, on the basis of Figure 2, we are more cautious about using these simulations to say very much about the relative space densities of different classes of spirals seen in deep images. It might be argued that a luminosity function peaked at $M^{*}$ is a generic consequence of sampling a Schechter function affected by Malmquist bias, so the overall shape of the luminosity distribution for the local galaxies in Figure 2 is also generically similar to what one also expects from a deep HST imaging campaign (in the absence of strong field galaxy evolution). However, the shape of this distribution is largely due to the absence of intrinsically faint galaxies at high redshifts, and the distribution of absolute magnitudes within a narrow redshift shell may look quite different from the absolute magnitude distribution for the sample as a whole. Since morphology is a strong function of rest wavelength, it is likely that any morphology-based campaign would isolate galaxies in redshift shells in order to construct fair samples to compare with local calibration data (e.g., van den Bergh et al. 2000). Clearly, then, for the specific purpose of calibrating the mix of different types of spirals fixed to a narrow redshift shell, an ideal local comparison sample should be drawn from an enormous parent population using a Schechter function–shaped distribution. We hope the sheer number of galaxies imaged by the Sloan Digital Sky Survey will soon make this possible, and at that point an extensive comparison between low-$z$ and high-$z$ Hubble-space distributions will become straightforward.

In the meantime, we emphasize that our goals in the present paper are much more limited. Our main goal is to determine the extent to which a typical local spiral galaxy is likely to be misclassified at high redshift (or, equivalently, how far a galaxy situated at a particular position in local Hubble space is likely to shift by $z = 0.7$). For this purpose, Figure 2 is less important than Figure 1, and the incompleteness of our BSGS sample at the faint end relative to the numbers expected from sampling a Schechter function–shaped distribution is not important so long as there are enough low-luminosity galaxies with a mix of morphological types in our sample to allow us to gauge how much a typical low-luminosity spiral is likely to move in a Hubble-space diagram as a function of resolution and signal-to-noise ratio. For example, since there are 28 galaxies fainter than $M_{B} = -19.5$ in the subset of the BSGS analyzed in this paper, and since about two-thirds of the SB subset of these would be classified SB at $z = 0.7$ in the HDF, we think it very unlikely that either low signal-to-noise ratio or resolution effects can explain the apparent absence of barred spirals in the HDF data.

Even after the numerical experiments described in this paper, we do remain concerned that cosmic variance might be the true explanation of the perceived absence of barred spirals at high redshifts. There is no known environmental dependence of bar strength on local galaxy density, though this possible dependence has not yet been definitively explored, and this is clearly a topic worthy of future study. It is conceivable that spirals in clusters might exhibit quite different bar-strength distributions as a result of numerous factors that might heat disks and suppress bar instabilities, such as tidal harassment (Moore et al. 1996) or gas stripping (Abraham et al. 1996a, 1996b). Furthermore, the volume encompassed to $z = 1$ in HDF-like observation is tiny. Assuming the non-evolving local luminosity function given by Gardner et al. (1997), only around 30 $L^{*}$ galaxies (of all morphological types, and with a range of inclinations) are expected to be visible (and, in fact, about this number is seen) in the redshift range $0 < z < 1$ in an HDF image. About 10 of these should be in the redshift range $0.6 < z < 0.8$. (In fact, only three spirals in this redshift range are seen in the northern HDF). Even after adding together both Hubble Deep Fields, the numbers remain appallingly low for addressing a topic as important as the possible disappearance of bars; clearly, more data are needed in order to conclusively rule out the possibility that cosmic variance could explain the absence of barred spirals in the Hubble Deep Fields.

8. CONCLUSIONS

We have studied the effects of image degradation on galaxy classification by (1) lowering resolution and by (2) increasing noise. Images were studied at both the noise level...
of the deep Hubble Deep Field images and at that of the shallower flanking field images. From comparison of the images of an unbiased sample of local ($z = 0.0$) galaxies with those of the same galaxies degraded to the appearance that they would have at $z = 0.7$, it is found that about two-thirds of all SB galaxies are still classified as SB or S(B) at the resolution and noise level of the HDF, dropping to around 50% in the flanking fields. Image degradation can account for some, but not all, of the observed (van den Bergh et al. 1996; Abraham et al. 1999) decrease in the fraction of SB galaxies with increasing redshift. Since luminosity classification is more challenging than determination of Hubble type, it is not surprising that only a fraction of the degraded images could be assigned DDO luminosity classifications. It is however of interest to note that the luminosity classifications that could be made on degraded images agree well with those made on the original full-resolution noise-free images. We conclude that the fraction of grand-design spirals appears to decrease with increasing redshift, although the number of galaxies observed at suitable signal-to-noise levels remains small and more observations are needed to better establish the demise of grand-design spirals with redshift.

On the basis of our simulations, it is clear that when local spiral galaxies are viewed at comparable resolution and noise levels to the HDF data, these systems are not systematically misclassified as peculiar. This lends credence to the notion that the fraction of peculiar disk galaxies is dramatically higher at $z \sim 0.7$ than it is at $z = 0.0$. In the study by van den Bergh et al. (2000) for HDF + FF galaxies at $0.60 < z < 0.80$, 17 out of 37 (46%) spirals are classified as peculiar. In other words, approximately half of all disk galaxies at look-back times of $\sim 8$ Gyr do not fit well into the Hubble classification system. This can be compared with the only 12% of artificially redshifted Sb + Sbc + Sc galaxies classified as peculiar in the present sample viewed at the same resolution and noise level. Among early-type spirals, the fraction of peculiar galaxies increases more slowly with redshift. These results suggest that (1) the fraction of intrinsically peculiar disk galaxies grows dramatically with increasing look-back time, and (2) the fraction of peculiar galaxies at $z \sim 0.7$ is much larger among late-type galaxies than it is among early-type spirals. It seems that late-type spirals approach their "normal" morphology more slowly than do galaxies of early type.

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