EVOLUTION OF GALAXY MORPHOLOGY

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Received ______________________; accepted ______________________

ABSTRACT

A strictly empirical review is given of presently available data on the evolution of galaxy morphology. From HST observations of distant galaxies and ground-based observations of nearby ones observed at the same rest-frame wavelength it is found that late-type (Sbc-Sc) galaxies evolve more rapidly with increasing redshift than do early-type (E-Sa-Sab) galaxies. Furthermore the fraction of peculiar objects, that cannot be shoehorned into the Hubble tuning fork classification scheme, increases rapidly with redshift. Unexpectedly it is found that, over a wide range of densities, the fraction of barred galaxies is independent of environment. However, this fraction of barred galaxies appears to decline rapidly with increasing redshift.

Don't assume anything - Look!

Gen. Joe Stilwell

1. INTRODUCTION

Theories of galaxy evolution remain speculative and uncertain. However, strong constraints on such theories are becoming available from the marvelous new imaging data on galaxy morphology at various redshifts that have have become available during the last seven years. Such observations show that most star formation in galaxies with $z < 1$ takes place in disks, whereas stars in objects with $z > 2$ occurs mainly in luminous "blobs" and chaotic structures. Furthermore the typical galaxy at $z > 2$ is, at any given time, undergoing a merger, whereas such major mergers are seen to be relatively rare at $z < 1$. Additionally, late-type galaxies are seen to change their appearance rapidly with increasing redshift, whereas the morphological evolution of early-type galaxies seems to be much slower. Unexpectedly the fraction of barred galaxies is observed to be a steeply decreasing function of redshift, while the fraction of nearby barred galaxies is found to be almost independent of their environment.

2. BARRED GALAXIES

Some time ago van den Bergh et al. (1996) noticed that barred galaxies appeared to be much rarer in the Hubble Deep Field than they are in nearby regions of the Universe. Making detailed corrections for band-shift effects, changes in resolution, and the increase of noise in observations of more distant galaxies, van den Bergh et al. (2002) were able to confirm the reality of this effect. As viewed in rest frame blue light, the fraction of barred galaxies appears to decrease from 23% at $z = 0.0$ to $\sim 4\%$ at $z \sim 0.7$. Possibly this decrease in the fraction of barred galaxies with increasing redshift is due to the fact that young, recently formed, spiral galaxies are still too chaotic (dynamically "hot") to undergo global bar-like instabilities. Another unexpected effect [see Table 1] is that the frequency of of bars in disk (S0-Im) galaxies appears to be almost independent of galaxy environment (van den Bergh 2002, and work in preparation).

Among 1103 nearby disk galaxies that have been observed with large reflecting telescopes (Sandage & Tammann 1981), it is found that $26 \pm 2\%$ are barred. This value does not appear to differ significantly from $32 \pm 5\%$ barred objects among 107 Coma S0-Sc galaxies with $m < 17.0$. Since the fraction of barred objects depends slightly on Hubble type it is, perhaps, fairest to compare the fraction of barred galaxies of types S0 + S0/a in the entire Shapley-Ames catalog directly with the corresponding fraction in the Coma cluster. For the entire Shapley-Ames catalog $25 \pm 4\%$ of 190 S0 + S0/a galaxies are barred, compared to $24 \pm 6\%$ of 62.5 such objects among galaxies with $m < 17.0$ in the Coma cluster. This result suggests that that the process that results in the formation of galactic bars is an internal one that is almost independent of galaxy environment.

3. PECULIAR GALAXIES

A galaxy is defined as being "peculiar" if it differs in some significant way from the prototypes used to define the Hubble tuning fork classification system. It is one of the beauties of Hubble's system that most luminous nearby galaxies fit it so well, and do not need to be "shoehorned" into the system. One of the most striking results obtained from the imaging of the Hubble Deep Field (Ferguson, Dickinson & Williams 2000) was that such a large fraction of the HDF(N) galaxies had peculiar morphologies. From my own classifications I find that the overall fraction of peculiar galaxies (as viewed in the restframe blue band) increases from 12% at z = 0.0 to 46% at $z \sim 0.7$. However, these overall figures are a bit misleading because of the difference that is observed between the way in which early-type and late-type galaxies "age". At $z \sim 0.7$ only ∼5% of E-S0-Sa galaxies appear to be peculiar. For comparison 69% of Sbc-Sc galaxies are peculiar at $z \sim 0.7$. Taken at face value this result suggests that late-type galaxies have required a longer time arrive at their present morphology than have systems of early type. Also the nature of the peculiarities seen in early-type galaxies are systematically different from those that are observed in late-type systems. In distant Sa-Sb spirals the arm structure is generally less well-developed than it is among nearby spirals with $z \sim 0$. On the other hand the peculiarity of late-type spirals at high redshifts is mainly due to the fact that their spiral structure is more chaotic than it is for nearby Sbc and Sc galaxies. A special kind of peculiarity occurs among spirals that are located in dense cluster environments (van den Bergh 1976). As a result of what is nowadays referred to as "galaxy harassment" (Moore et al. 1996) the spiral arms of tidally interacting early-type galaxies (and galaxies in rich clusters) have a "fuzzy" appearance. [In extreme cases the spiral structure becomes "anemic".] On the other hand the spiral arms of late-type interacting spirals take on a “knotty” morphology, which is presumably due to an enhanced formation rate of clusters and associations.

4. THE MADAU PLOT

Perhaps the most striking feature of galaxy morphology and star formation is that most stars at $z < 1$ appear to be forming in disks. On the other hand the majority of stars in objects with $z > 2$ seem to form in luminous clumps or in chaotic structures. Possibly the change in slope of the Madau (1997) plot near $z \sim 1.5$ is due to this transition from chaotic/clumpy star formation at high redshifts to star creation in disks among the majority of nearby galaxies.

5. MERGERS

On deep exposures with the HST the surface density of galaxies is high. As a result many galaxies are members of optical, i.e. nonphysical pairs. One can try to circumvent this problem by only accepting those objects which either (1) exhibit (tidal) distortions, or (2) galaxies with physically overlapping main bodies as merger candidates. Adopting this definition it is found that only ∼5% of the galaxies in the HDF(N) +HDF(S) that have $z < 1.2$ are merger candidates. On the other hand it turns out that ∼57% of the objects with $z > 2.0$ are merger candidates. In other words most galaxies at $z > 2$ are, at any given time, involved in a merger with a luminous (massive) companion, whereas nearby galaxies are typically single. It is noted in passing that only 1.5% of the galaxies with $m < 17.0$ in the Coma cluster appear to be merging (or have double or multiple cores). Presumably this low merger frequency is a direct consequence of the very high (1038 ± 60 km/s, Colless & Dunn 1996) velocity dispersion in the Coma cluster.

6. CONCLUSIONS

Perhaps the most important insight that has been obtained in recent times is that galaxy morphology depends strongly on both the environment and on the redshifts of galaxies. The Hubble tuning fork classification system is strictly applicable only to nearby galaxies with $z < 0.5$, with bars apparently becoming ever less frequent with increasing redshift. Furthermore The Hubble system becomes degenerate in very dense environments where the majority of galaxies are of Hubble types E, S0 and SB0.

Table 1. DEPENDENCE OF FRACTION OF BARRED GALAXIES ON ENVIRONMENT

Enviroment	Percentage of barred galaxies
Nearby field	25 ± 3
Nearby groups	19 ± 4
Nearby clusters	28 ± 3
Coma	32 ± 5

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This manuscript was prepared with the AAS LaTeX macros v5.0.