REVIEW: ASTROPHYSICS

The Morphological Evolution of Galaxies

Roberto G. Abraham[1]* and Sidney van den Bergh[2]

Many galaxies have taken on their familiar appearance relatively recently. In the distant Universe, galaxy morphology deviates significantly (and systematically) from that of nearby galaxies at redshifts (z) as low as 0.3. This corresponds to a time $\sim 3.5 \times 10^9$ years in the past, which is only $\sim 25\%$ of the present age of the Universe. Beyond $z = 0.5$ (5×10^9 years in the past), spiral arms are less well developed and more chaotic, and barred spiral galaxies may become rarer. At $z = 1$, around 30% of the galaxy population is sufficiently peculiar that classification on Hubble's traditional "tuning fork" system is meaningless. On the other hand, some characteristics of galaxies have not changed much over time. The space density of luminous disk galaxies has not changed significantly since $z = 1$, indicating that although the general appearance of these galaxies has continuously changed over time, their overall numbers have been conserved.

Nearby galaxies are usually classified on the basis of a scheme originally proposed by Edwin Hubble in 1926 (*1*). This "tuning fork" classification system characterizes galaxies with reference to a set of bright nearby standard galaxies. In Hubble's scheme, galaxies are divided into ellipticals and spirals. Spiral galaxies are subdivided into unbarred (S) and barred (SB) categories, which define the tines of the tuning fork. Along each tine, galaxies are further subdivided according to the tightness and fine structure of their spiral arms, which changes monotonically along the tuning fork in step with the fraction of light in the central bulge of the galaxy. These subcategories are denoted Sa, Sb, and Sc (SBa, SBb, SBc in the case of barred spirals). A catch-all category for irregular galaxies is also included.

More than 90% of luminous nearby galaxies fit within this system. Intrinsically faint galaxies, such as many of the dwarf galaxies in the Local Group (the agglomeration of galaxies within 1.3 Mpc of the Milky Way Galaxy), cannot be slotted into the standard classification system. Such faint dwarf galaxies vastly outnumber the bright galaxies described by the Hubble sequence. However, these dwarfs contribute little to the total mass budget of the galaxy population and they are difficult to detect at large distances.

Modern attempts to understand the physical meaning of Hubble's classification system are based on the idea that most matter in the Universe is not in stellar or gaseous form, but is instead composed of dark matter. Dark matter does not emit or absorb radiation, and it can only be detected by its gravitational effects on spectroscopically observed galaxy rotation curves or by gravitational bending of galaxy images ("gravitational lenses"). Some fraction of the dark matter in the Universe is made up of baryons (protons, neutrons, and related particles), but from the relative abundances of elements formed in the Big Bang, well over 90% must be in a nonbaryonic form (*2*). Theoretical work relies on the hypothesis that dark matter and galaxies are linked, because gravitating concentrations of dark matter originating soon after the Big Bang are responsible for the formation of galaxies. In this view, small concentrations of dark matter grow slowly at first, and are then gradually compressed by self-gravity. However, when the concentrations reach a critical density (about 200 times the mean background density of the Universe), they undergo a catastrophic nonlinear collapse, which results in the formation of an extended "halo" of dark matter. Over time these halos clump together under their mutual gravitational attraction, merging to form a hierarchy of larger halos. The rate of cooling and angular momentum of hydrogen gas drawn into these large halos governs the assembly of normal galaxies and, ultimately, their morphology.

This new paradigm has transformed our view of galaxy evolution (Fig. 1). It is now believed that most visible galaxies are embedded in much larger and more massive dark-matter halos that detached from the expanding cosmic plasma (created in the Big Bang) at early times. Furthermore, galaxies are no longer viewed as growing in isolation, but rather as being linked into a web of large-scale structure, which originated in the density fluctuations traced by the surface brightness variations now seen in the cosmic microwave background (*3–6*). Observations of galaxy morphology now span about 70% of the total age of the Universe and allow this paradigm to be tested.

Caveats

Morphological classification of galaxies at redshifts near $z = 1$ is challenging because the number of pixels per image, relative to images of nearby galaxies, may be smaller by a factor of $\leq \sim 100$. Classification at $z \sim 1$ therefore represents a considerable extrapolation from similar work at $z \sim 0$. Caution must be exercised to avoid resolution-dependent effects that might affect images of distant galaxies more than they do nearer galaxies. The slight "undersampling" of images from Hubble Space Telescope (HST) Wide-Field/Planetary Camera 2 makes the classification of very compact galaxies (such as distant ellipticals) particularly difficult. Another problem is that it is often tempting to "shoehorn" slightly peculiar distant galaxies into the familiar Hubble classification system. As a result, one classifier may regard a certain object as, say, a somewhat peculiar variant of a regular spiral galaxy (designated "Spec" in many catalogs of local galaxies and considered to lie within the Hubble sequence), whereas another classifier may classify the same object as peculiar (i.e., outside the Hubble sequence altogether). Such taxonomical inexactitude is probably inherent in the subjective nature of visual classification and is the major reason for the rising popularity of computer-based objective classification schemes based on the measurement of quantitative parameters. However, such objective schemes do not yet encompass the full richness of galaxy forms. Current computer-based classification systems only allow grouping of galaxies into broad categories that most visual morphologists would consider too coarse (*7, 8*). For example, no quantitative scheme can currently distinguish between physically distinct subcategories of spiral structure (*9*).

Another important caveat that applies to all current studies of distant galaxy morphology is that the number of galaxy images available for study is small. Each Hubble Deep Field (HDF) contains ~ 3000 galaxies or galaxy fragments, but only a few hundred of these are large enough, bright enough, and near enough to allow reliable morphological classification; of these, only ~ 70 are sufficiently well resolved (and are viewed at sufficiently low inclinations to the line of sight) to allow substructure such as bars and weak spiral arms (if present) to be detected. Also,

[1]Department of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 3H8, Canada. [2]Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, British Columbia V9E 2E7, Canada.

*To whom correspondence should be addressed. E-mail: abraham@astro.utoronto.ca

as a result of the morphology-density relation (*10*), narrow-field observations such as those undertaken with HST may be significantly biased by galaxy environment. For example, elliptical galaxies are expected to be over-abundant in those parts of the line-of-sight that pass through, or close to, clusters of galaxies.

A final complication is introduced by the fact that distant galaxies are seen at a range of redshifts. Therefore, observations made in a single filter probe each galaxy at a wavelength different from that of the same filter in the rest frame (i.e., the frame of reference in which the galaxy is stationary with respect to the expansion of the Universe). This poses a

problem for morphologists, because the appearance of a galaxy can vary strongly with wavelength. In the ultraviolet (UV), a galaxy's light comes mainly from hot young stars, which are often distributed in clumpy irregular knots of star formation. At optical wavelengths, stars on the stellar main sequence dominate, and galaxies take on their most familiar appearance. In the infrared (IR), most of the flux is usually from evolved old stars, which are quite uniformly distributed, so galaxies appear smoother than at optical wavelengths. As a result, identical galaxies appear different at different redshifts. The importance of this effect (known as the "morphological K-correction") depends rather strongly on the distance at which the galaxy is seen. For galaxies with redshifts $z < 0.8$ [i.e., for galaxies seen at look-back times less than about halfway back to the Big Bang (*11*)], observations made with HST using the F814W filter (commonly used for morphological work) correspond to observations made at familiar optical wavelengths in the galaxy's frame of reference. Thus, the effects of morphological K-corrections are quite benign at $z < 0.8$, and much work on galaxy morphology has focused on this "safe" redshift range. At redshifts $z > 0.8$, galaxies viewed with the F814W filter are being seen at UV wavelengths in the rest frame. Unfortunately, rather little is known about the appearance of nearby galaxies in the UV, because our atmosphere is opaque to UV radiation, and only rather small UV imaging surveys have been undertaken from space. It is clear that some nearby galaxies that appear optically normal appear strange in the UV (*12, 13*). Consequently, galaxies at $z > 0.8$ are best studied in the IR at wavelengths greater than 1 μm in order to undertake fair comparisons with local studies made at optical wavelengths (*14*). HST had only a rather limited capability to undertake such observations, using the short-lived Near Infra-Red Camera and Multi-Object Spectrometer (NICMOS).
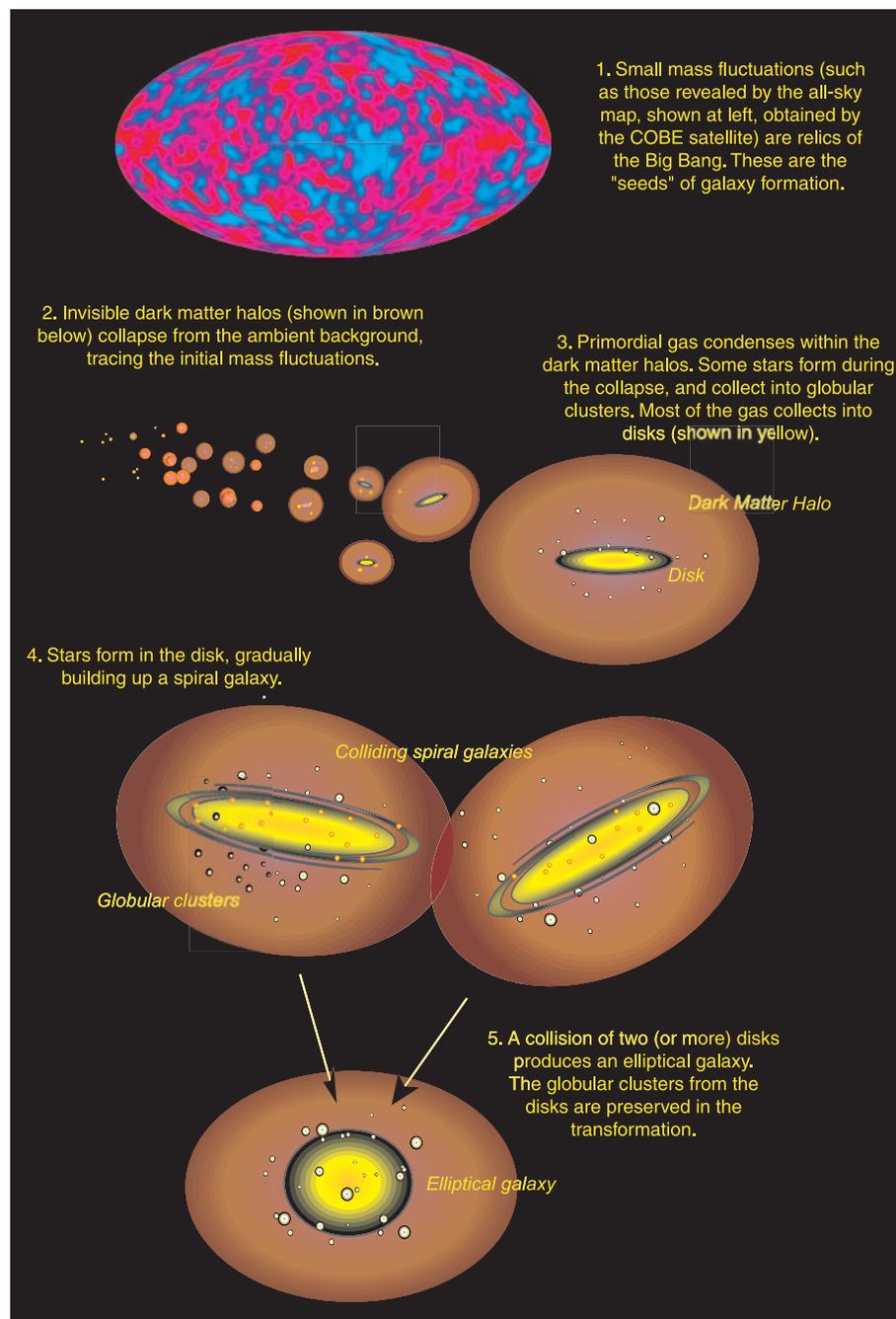
Morphological Classifications of Distant Galaxies

The existence of a population of morphologically peculiar galaxies at high redshifts was first suspected on the basis of HST observations as early as 1994 (*15–19*). Much of this early work proceeded hand in hand with improved attempts to quantify galaxy morphology using automated morphological classification schemes, as fast and robust replacements for traditional visual classifications. Present state-of-the-art automatic classification systems can group galaxies into broad categories (such as spirals, ellipticals, and peculiars) as reliably as can a visual classifier (*7, 20, 21*), and these systems are in principle extensible to encompass wholly new classes

1. Small mass fluctuations (such as those revealed by the all-sky map, shown at left, obtained by the COBE satellite) are relics of the Big Bang. These are the "seeds" of galaxy formation.

2. Invisible dark matter halos (shown in brown below) collapse from the ambient background, tracing the initial mass fluctuations.

3. Primordial gas condenses within the dark matter halos. Some stars form during the collapse, and collect into globular clusters. Most of the gas collects into disks (shown in yellow).

Dark Matter Halo

Disk

4. Stars form in the disk, gradually building up a spiral galaxy.

Colliding spiral galaxies

Globular clusters

5. A collision of two (or more) disks produces an elliptical galaxy. The globular clusters from the disks are preserved in the transformation.

Elliptical galaxy

Fig. 1. Schematic illustration of the formation of galaxies in the hierarchical formation model. The time scale for the various phases shown in the illustration depends on cosmological parameters (i.e., the value of the Hubble constant, and the total mass-energy of the Universe contained in both dark matter and dark energy). For example, in an accelerating Universe most elliptical galaxies form at redshifts $z > 1$, while in a decelerating Universe most ellipticals form at $z < 1$. It is worth noting that morphological transformations are cyclical in this model. Some elliptical galaxies formed by the collision of spirals will slowly accrete gas from the field, thus growing a new disk, and ultimately being transformed back into spiral galaxies with prominent nuclear bulges.

of galaxies beyond those included within the tuning fork paradigm.

Although these early HST studies suggested that extending the low-redshift tuning fork paradigm to high redshifts would prove difficult, the ultimate futility of this task only became apparent when the HDF images were released (Fig. 2). At the limit to which morphological classification is reliable in the deep fields (variously quoted as between $I = 25$ mag and $I = 26$ mag), around 30% of the galaxies are classified as "strongly peculiar or merging"—that is, about 30% of the galaxies fall outside the conventional framework (20, 22, 23). Most studies find little evidence for evolution in the space density of elliptical galaxies [with the exception of (24)]. But, as is the case with spiral galaxies, the internal characteristics of elliptical galaxies do show trends with redshift. The most prominent of these is an increasing proportion of elliptical galaxies with blue cores in the distant Universe (25), which indicates the presence of some hot young blue stars in these old galaxies.

Imaging studies allow trends to be established as a function of galaxy brightness, but more physically based investigations of galaxy morphology require that the redshifts of the galaxies be known. This is a formidable challenge; galaxies can be detected on charge-coupled device images down to much fainter levels than can be probed spectroscopically, because in the latter case light is being dispersed, so Poisson noise is larger relative to the signal of interest. One rather successful technique for dealing with this difficulty has been to estimate redshifts from galaxy colors (26). Morphological investigations using these "photometric redshifts" (24, 27) have confirmed and solidified the statistical conclusions from earlier imaging studies of galaxies that had no photometric redshift information; this made it possible to draw galaxy samples from redshift ranges immune to the effects of morphological K-corrections. But because photometric redshift techniques rely, at a basic level, on assumptions regarding the possible spectra of galaxies and on the nature of systematics that may alter such spectra (such as the form of the dust extinction curve), they are only fairly crude estimators ($\Delta z \sim 0.1$ for blue galaxies, $\Delta z \sim 0.04$ for red galaxies) of the true redshifts of distant galaxies (26). Morphological investigations of large samples of objects of known redshift became feasible when Brinchmann *et al.* (28) obtained HST images for 341 galaxies of known redshift from the Canada-France Redshift Survey. Results from this investigation agree with earlier results (17, 20, 29). Around 30% of galaxies at $z = 1$ are morphologically peculiar, and these authors found that the fraction of galaxies with irregular morphology increases with redshift beyond the range that is expected on the basis of the systematic misclassifications of spiral
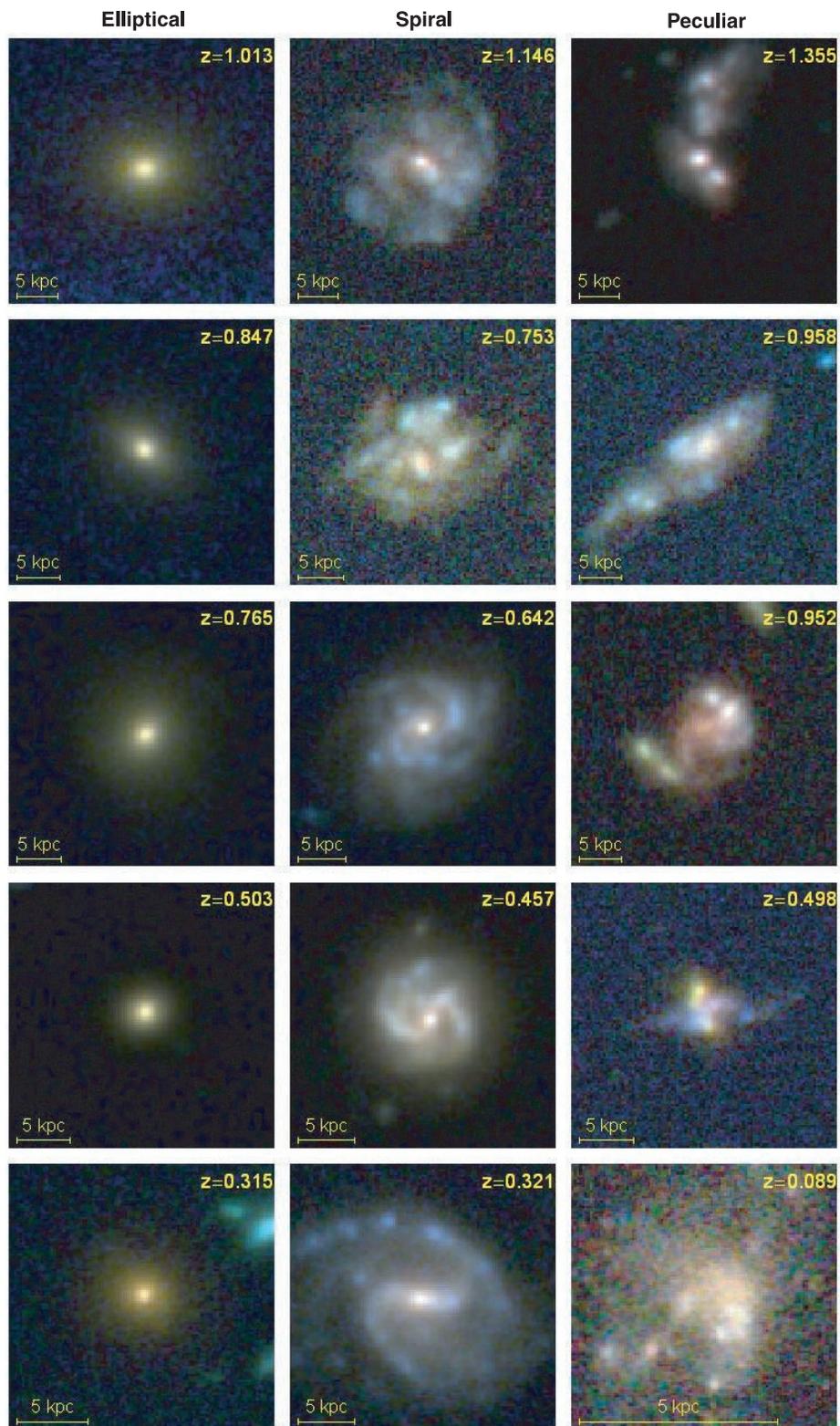

Fig. 2. Montage of typical elliptical, spiral, and peculiar galaxies in the Northern and Southern HDFs, imaged by the HST. The images are sorted by redshift (local galaxies at bottom, distant galaxies at top). Color images were constructed by stacking images obtained through blue, yellow, and near-IR filters. Note the gradual loss in the organization (and the increase in the fragmentation) of spiral arms in the spirals. Barred spirals (such as the example shown in the bottom row) become rare beyond $z = 0.5$. The physical nature of most of the peculiar galaxies in the far right column is poorly understood. The exception is the object at the lower right corner, which is a dwarf irregular, a class of objects common in the local Universe. In Fig. 3, we speculate on the possible nature of two other galaxies in the far right column.

galaxies introduced by band-shifting effects. Furthermore, their data for the frequency with which elliptical galaxies are distributed over the redshift range $0.0 < z < 1.2$ were found to be consistent with expectations for scenarios with little or no morphological evolution for these objects.

The trends described so far have been based on rather coarse automated morphological classifications. More fine-grained "precision morphology" (which can subdivide spiral galaxies into various subclasses, for example) still requires a trained human eye, and also requires complete redshift information and multifilter data in order to synchronize data to a uniform rest wavelength. The largest such investigation (30) has been based on the Caltech Faint Galaxy Redshift Survey (CFGRS), a deep follow-up redshift survey centered on the Northern HDF, but also con-

taining redshifts for galaxies in the nearby HDF "flanking fields." This study suggests the following picture: (i) The fraction of early-type (E-Sab) galaxies remains approximately constant over the range $0 < z < 1$, in agreement with earlier studies (28, 31). (ii) The fraction of intermediate/late-type (Sb-Ir) galaxies drops by a factor of ~2 over this redshift range, presumably because many late-type galaxies viewed at a look-back time of ~8 Gy (8×10^9 years) have been classified as "peculiar" or "merger." (iii) The fraction of such peculiar or merging galaxies exhibits a monotonic increase (5% at $z \sim 0$, 10% at $z \sim 0.4$, 19% at $z \sim 0.7$, and 30% at $z \sim 0.95$). These numbers are in quite good agreement with the corresponding numbers inferred from measurements based on automated classifications, although it should again be emphasized that the numbers of galaxies in

all such studies are small, and the conclusions that can be drawn from them are correspondingly uncertain. It is worth noting that the merger rate estimated from the HDF on the basis of morphological considerations is in reasonable agreement with the merger rate inferred from HST imaging of the CFGRS fields (32) and from pair counts at lower redshifts (33).

Beyond $z \sim 1$, one must observe galaxies in the IR in order to study them at familiar optical wavelengths in their rest frames. The NICMOS camera on HST had this capability, although its small field of view and limited lifetime (34) meant that relatively few $z > 1$ field galaxies were observed in the near-IR before the instrument ceased functioning. However, over the short lifetime of this camera, it was possible to demonstrate (14, 35, 36) that most galaxies with peculiar optical morphologies remain peculiar when viewed in the near-IR, at least out to $z = 3$ (37). It follows that the strange appearance of these objects is not merely the consequence of "morphological K-corrections" (i.e., of observing only irregularly distributed sites of star formation at rest UV wavelengths while missing the bulk of the galaxy). The peculiar appearance of these objects reflects a genuinely irregular structural state in these galaxies. However, in the most distant objects (i.e., at $z > 3$), it may be the case that we are only seeing the tip of the baryonic mass iceberg (i.e., only the youngest stars in the galaxies, grouped together in irregular star formation complexes).

Returning our consideration to the luminous peculiar galaxies seen at lower redshifts ($1 < z < 3$), it is fair to say that little is known about the nature of these objects. A large fraction may be galaxy mergers or collisions, because the abundance of colliding galaxies is expected to increase in the distant Universe (38), although statistical analyses of the merger rate as a function of cosmic epoch at $z > 1$ have not been undertaken. Most objects classified as "mergers" in deep HST images are only merger candidates. Radial velocity differences of less than a few hundred km s^{-1}, and/or evidence for tidal distortions (such as tails), are required to be sure that merger candidates are indeed physically interacting/merging objects. However, the evidence for mergers is fairly suggestive, because some of the strangest-looking systems can be matched to counterparts among nearby merging systems (Fig. 3). But even if most of the high-redshift peculiar galaxies turn out to be distorted as a result of mergers or collisions, this is probably not the whole story, because some peculiar systems exhibit properties that are not seen in nearby mergers (33).

Two types of observations are needed to understand the nature of the morphologically peculiar galaxy population. First, rest-
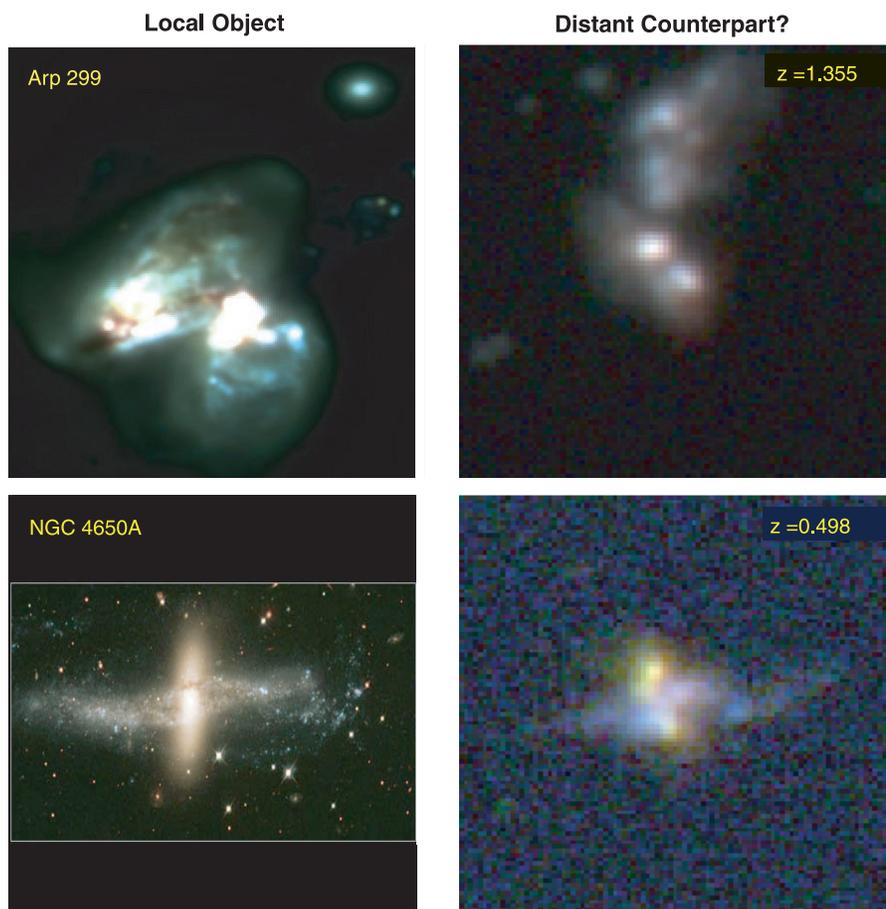
Local Object

Distant Counterpart?

Fig. 3. Some speculations on the nature of high-redshift peculiar galaxies. Top row: As pointed out in (40), the nearby local merging starburst galaxy Arp 299 shares many of the morphological and star-formation characteristics of "chain-like" peculiar galaxies, such as the example (HDFN_J123652.78+621354.3) shown at right. Although the correspondence is not exact (chain-like peculiars exhibit more components than are typically seen in local starbursts and sometimes show a curious synchronization of internal colors), local starbursts remain the closest match to many distant systems. Bottom row: Classes of merging galaxies that are exceedingly rare in the local Universe may be responsible for some of the oddest systems seen in the HDFs. For example, the "polar ring" galaxy NGC 4650A bears a close resemblance (in terms of both morphology and relative color) to the distant galaxy (HDFN_J123652.88 + 621404.8) shown at bottom right. Galaxy collisions can produce a rich variety of morphologically peculiar galaxies, many of which do not resemble "textbook" mergers (i.e., a pair of objects with obvious tidal tails). [NGC 4650A image courtesy of the Hubble Heritage Team (STScI/AURA/NASA)]

frame IR imaging is needed to look for the presence of red light from evolved stars in these galaxies. Such data will constrain the ages of the underlying stars in the galaxies independently from their morphologies. Such data will also determine whether the objects are genuinely protogalactic (i.e., formed exclusively from young stars) or whether they correspond to a stage in the growth of evolved galaxies. Second, dynamical studies of high-redshift objects are needed to distinguish merger remnants from bona fide singular new classes of objects. Such studies are in their infancy. On the basis of early work on the so-called "Lyman break" population at $z > 2.3$, much of which is morphologically peculiar, it seems that at least some of the more distant morphologically peculiar systems do not exhibit even the most basic ordered motions expected from rotating disks (*39*). Some of these objects could be distant analogs to the most extreme local star-bursting galaxies, whose morphological characteristics originate in the collapse along filaments of gas driven by energetic "super winds" (*40–42*).

Comparison with Numerical Simulations

The computational state of the art has evolved to the point where numerical simulations of galaxy evolution can be linked with cosmological simulations for the growth of large-scale structure (such as galaxy clusters). Consequently, the morphological evolution of galaxies can now be explored in a proper cosmological context. However, the resolution of such simulations remains rather poor ($<10^5$ particles per galaxy). Simulations with higher resolution have been undertaken with pure *n*-body gravitational codes, at the expense of neglecting important gas-dynamical effects. Alternatively, simulations can be constructed to study individual galaxies, or small systems of galaxies, essentially in isolation. Such simulations may be constructed with up to 10^8 particles per galaxy (i.e., within a factor of 100 of the number of stars in a typical luminous galaxy). This class of simulations suggests that elliptical galaxies could form from the collision of spirals (*43, 44*). An oft-cited prediction of hierarchical models is that elliptical galaxies should become increasingly rare with increasing redshift, dropping to 30% their local space density in co-moving coordinates (i.e., coordinates expanding at the same rate of expansion as the Universe itself) by $z \sim 1$. This evolution can probably be excluded on the basis of existing data [but see (*24*) for a contrary opinion]. However, models that include a cosmological constant now push the epoch for most elliptical formation to $z > 1$, which is beyond the redshift at which an unbiased inventory of ellipticals exists. Therefore, merger-induced formation of field ellipti-

cals remains the favored theoretical model, although this scenario still needs observational verification.

The present generation of *n*-body/gas-dynamical models fails to account for a number of important observations. Dark halos appear to have constant-density cores rather than the predicted power law–like cusps, and the models predict an order of magnitude too many companions for giant galaxies. However, the most important problem is their failure to correctly account for galaxy sizes. To date, all cosmological codes (i.e., those that begin with a fluctuation spectrum for dark-matter halos at high redshift, and evolve this forward while collapsing gas into these halos to form galaxies) predict that luminous galaxy disks around $z \sim 1$ should be far smaller than are typically seen. The observational constraint is actually rather severe: The space density of large disks at $z \sim 1$ is similar to that seen in the nearby Universe (*45*). "Semi-analytical" models (which blend the predictions of *n*-body codes for the growth of dark-matter halos with phenomenological models for the growth of galaxies within these halos) are more successful in predicting galaxy sizes as a function of redshift, as well as in modeling the changing morphological mix with redshift. A criticism of these models is that they adopt rather crude scaling relations to describe important aspects of physics that cannot be treated from first principles (e.g., stellar winds expelled from the disks of galaxies, which lead to star formation by a complex feedback process).

In summary, at present the numerical models that attempt to model the physics of galaxy formation from first principles do not have sufficient resolution, whereas those that attempt to sidestep problems with resolution oversimplify the systems. At present, no class of models has accounted for detailed evolution of the internal structures of galaxies. An interesting link between dynamical models and morphology is the predicted evolution of bars, because these features are sensitive to the dynamical state of galaxy disks and are bright enough to be detectable in distant galaxies. In an inspection of the Northern HDF images, van den Bergh suggested that barred spirals were unexpectedly rare at high redshifts (*19*). Support has been lent to this observation by (*46*), which shows that the frequency of SB galaxies at $0.6 < z < 0.8$ is only $\sim$5% in the HDFs, versus 21 to 34% among

nearby Shapley-Ames galaxies. Both of these results are based on small numbers of galaxies and need to be tested against larger samples (*47*).

Discussion

Table 1 provides a summary of our interpretation of the "key ages" in the morphological development of galaxies to $z = 1$. Beyond this redshift, the galaxy population appears so peculiar that we feel much more IR imaging data (probing galaxies at optical wavelengths in the rest frame) are needed to draw any conclusions beyond the basic observation that luminous galaxies have changed a great deal in appearance in the last 8 billion years. Perhaps the most surprising result from Table 1 is that the systematics of galaxy morphology still appear to be evolving rapidly at the present time. This is most clearly illustrated by the fact that grand-design spirals are found to be rare before $z \sim 0.3$, corresponding to a look-back time of only 3.5 Gy. By the time that one looks back beyond $z = 0.5$ (5 Gy), almost all spiral structure seems to be less well developed (or more chaotic) than it is among nearby galaxies.

Explaining why the Hubble classification scheme appears to "evaporate" at redshifts $z > 0.3$ is a challenge that can only be met by a greater understanding of galaxy dynamics at high redshifts. The gas fraction in typical spiral galaxies may have decreased by a large fraction between $z = 1$ and $z = 0$, and encounters with giant molecular clouds, spiral arms, and perhaps clumps in the dark-matter halo may have increased the velocity dispersion within the disk at high redshifts. Fuchs and von Linden (*48*) and Fuchs *et al*. (*49*) have suggested that either of these effects would affect the stability of spiral disks in the distant past, but the data simply do not yet exist to allow astronomers to determine whether either of these effects plays a dominant role. At this stage, all that is clear is that the morphology of spiral galaxies is evolving rapidly and systematically, even at quite low redshifts. Familiar types of galaxies, such as barred and grand-design spirals, appear to be relatively recent additions to the extragalactic zoo. The nature of the many morphologically peculiar galaxies at high redshift remains a complete mystery. These objects might be mergers, protogalaxies, new classes of evolved systems, or a combination of all three.

Table 1. Summary of key ages in galaxy morphology to $z = 1$.

Redshift	Look-back time	Key developments in galaxy morphology
$z < 0.3$	$< \sim$3.5 Gy	Grand-design spirals exist. Hubble scheme applies in full detail.
$z \sim 0.5$	$\sim$5 Gy	Barred spirals become rare. Spiral arms are underdeveloped. The bifurcated "tines" of the Hubble tuning fork begin to evaporate.
$z > 0.6$	$>$6 Gy	Fraction of mergers and peculiar galaxies increases rapidly. By $z = 1$, around 30% of luminous galaxies are off the Hubble sequence.

We are only beginning to glimpse the morphology of galaxies in the distant Universe, and we are groping to fit them into a physically meaningful organizational structure. Progress will require astronomers to devise better and more fully quantitative means of characterizing the (increasing) peculiarity of galaxies in the distant Universe. As a first step, one might follow in the footsteps of Morgan (*50, 51*), Doi *et al.* (*52*), and Abraham (*19, 53*), who used central concentration of light as a classification parameter. Other statistical measures that could turn out to be useful for the classification of galaxies at large look-back times are rotational asymmetry (*20, 54*), "blobbiness" and filling factor of isophotes (*55*), and central offset of the galaxy nucleus. Many of these are likely to be correlated with both the ages and star-formation properties of galaxies. The physical importance of these parameters can be better understood by explicit reference to *n*-body/gas-dynamical simulations. With the IR-optimized Next Generation Space Telescope on the horizon, it will also be of great interest to extend rest-wavelength optical morphological work to distant objects at ever greater look-back times that can best be observed in the IR (*56*). Extending morphological studies to the rest-frame mid-IR has a number of important benefits: Dust obscuration is reduced, and the link between morphology and underlying stellar mass (best traced by old stars) becomes more direct.

It seems conceivable that in some of the distant morphologically peculiar objects in the HDFs, we are witnessing an early stage in the life cycle of present-day luminous galaxies, in which most of their baryons become locked up in stars rather than in primordial gas. This is the classic description of a protogalaxy. Ground-based spectroscopic surveys show that over the redshift range $0 < z < 4$, most star formation is occurring in massive galaxies (*57, 58*). However, by $z = 10$ the age of the Universe is rapidly approaching the dynamical time scale of a large galaxy ($\sim$ few 10^8 years), whereas stellar evolutionary time scales for massive stars remain much shorter (10^4 to 10^7 years). Most of the stars that exist at these high redshifts may not have had time to come together to form large galaxies. Indeed, deep HST images are littered with small faint objects that might be more properly considered galaxy fragments (*59, 60*). Their distances are unknown; only the brightest 5% of objects on the HDFs have known redshifts. It is conceivable that these systems—and not the morphologically bizarre, luminous galaxy population that has been the focus of much of this review—represent the true first appearance of galaxies in the Universe. In any case, these faint galaxies are barely resolved, and we have

no idea what they look like; they are both too faint and too small to classify with HST. They remain outside the realm of the morphologist. At present they define, in the words of Hubble, the "dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial" (*61*).

References and Notes

1. E. P. Hubble, *Astrophys. J.* **64**, 321 (1926).
2. In the last 3 years, astronomers have also found evidence for "dark energy," a counterpart to dark matter that may be responsible for an accelerating expansion of the Universe.
3. J. Peacock, *Cosmological Physics* (Cambridge Univ. Press, Cambridge, 1999).
4. A. Balbi *et al.*, *Astrophys. J.* **545**, L1 (2000).
5. P. de Bernardis *et al.*, *Nature* **404**, 955 (2000).
6. C. B. Netterfield *et al.*, in preparation (available at http://xxx.lanl.gov/abs/astro-ph/01004460).
7. A. Naim *et al.*, *Mon. Not. R. Astron. Soc.* **274**, 1107 (1995).
8. R. G. Abraham, *Astrophys. Space Sci.* **269**, 323 (1999).
9. Quantitative investigations of spiral structure at high redshifts may become possible in the near future, however, using Fourier decomposition techniques [R. Windhorst, S. Odewahn, C. Burg, S. Cohen, I. Waddington, *Astrophys. Space Sci.* **269**, 243 (1999)].
10. A. Dressler, *Astrophys. J.* **236**, 351 (1980).
11. All ages used in the present paper are based on a cosmology in which the Hubble parameter is $H_0 = 70$ km s^{-1} Mpc^{-1}, the contribution of baryonic and dark matter to the critical closure mass-energy density of the Universe is $\Omega_M = 0.3$, and the contribution of dark energy is manifested by a cosmological constant with density is $\Omega_\Lambda = 0.7$. In this cosmology, the present age of the Universe from the time of the Big Bang is 13.5 Gy.
12. P. M. Marcum *et al.*, *Astrophys. J. Suppl.* **132**, 129 (2001).
13. M. Giavalisco, C. C. Steidel, M. E. Dickinson, K. L. Adelberger, M. Pettini, in *The Ultraviolet Universe at Low and High Redshift: Probing the Progress of Galaxy Evolution*, W. H. Waller, M. N. Fanelli, J. E. Hollis, A. C. Danks, Eds. (American Institute of Physics Press, College Park, MD, 1997), p. 221.
14. M. Dickinson, in *After the Dark Ages: When Galaxies Were Young (the Universe at $2 < z < 5$)*, 9th Annual October Astrophysics Conference in Maryland, 12 to 14 October 1998, College Park, MD, S. Holt, E. Smith, Eds. (American Institute of Physics Press, College Park, MD, 1999), p. 122.
15. L. L. Cowie, E. M. Hu, A. Songaila, *Nature* **377**, 603 (1995).
16. _____, *Astron. J.* **110**, 1576 (1995).
17. K. Glazebrook, R. Ellis, B. Santiago, R. Griffiths, *Mon. Not. R. Astron. Soc.* **275**, L19 (1995).
18. S. P. Driver, R. A. Windhorst, R. E. Griffiths, *Astrophys. J.* **453**, 48 (1995).
19. R. G. Abraham *et al.*, *Astrophys. J.* **107**, 1 (1996).
20. R. G. Abraham *et al.*, *Mon. Not. R. Astron. Soc.* **279**, L47 (1996).
21. A. Naim, K. U. Ratnatunga, R. E. Griffiths, *Astrophys. J.* **111**, 357 (1997).
22. S. C. Odewahn, R. A. Windhorst, S. P. Driver, W. C. Keel, *Astrophys. J.* **472**, L13 (1996).
23. S. van den Bergh *et al.*, *Astron. J.* **112**, 359 (1996).
24. F. R. Marleau, L. Simard, *Astrophys. J.* **507**, 585 (1998).
25. F. Menanteau, R. G. Abraham, R. S. Ellis, *Mon. Not. R. Astron. Soc.* **322**, 1 (2001).
26. D. W. Hogg *et al.*, *Astron. J.* **115**, 1418 (1998).
27. S. P. Driver *et al.*, *Astrophys. J.* **496**, L93 (1998).
28. J. Brinchmann *et al.*, *Astrophys. J.* **499**, 112 (1998).
29. S. P. Driver *et al.*, *Astrophys. J.* **449**, L23 (1995).
30. S. van den Bergh, J. G. Cohen, D. W. Hogg, R. Blandford, *Astron. J.* **120**, 2190 (2000).
31. It should be emphasized that around 30% of the

objects classified as ellipticals at high redshifts do not have the uniform red colors of local elliptical galaxies. Perhaps some of the high-redshift "blue ellipticals" are related to a class of objects known as "blue compact galaxies" in the nearby Universe [M. A. Bershady, A. Jangren, C. J. Conselice, *Astron. J.* **119**, 2645 (2000)].
32. O. Le Fevre *et al.*, *Mon. Not. R. Astron. Soc.* **311**, 565 (2000).
33. R. G. Abraham, in *IAU Symp. 186: Galaxy Interactions at Low and High Redshift* (1999), p. 11.
34. NICMOS was available for a 2-year window of observations. After a 3-year hiatus, NICMOS will once again become available after the next HST servicing mission.
35. H. C. Ferguson, M. Dickinson, R. Williams, *Annu. Rev. Astron. Astrophys.* **38**, 667 (2000).
36. C. Conselice, *Astrophys. Space Sci.* **269–270**, 585 (1999).
37. See supplemental figure on *Science* Online at www.sciencemag.org/cgi/content/full/293/5533/1273/DC1.
38. Because the proper volume between galaxies diminishes with redshift as $(1 + z)^{-3}$, distant galaxies are packed more tightly into a given volume of space.
39. M. Pettini *et al.*, in press (available at http://xxx.lanl.gov/abs/astro-ph/0102456).
40. J. E. Hibbard, W. D. Vacca, *Astron. J.* **114**, 1741 (1997).
41. _____, M. S. Yun, *Astron. J.* **119**, 1130 (2000).
42. Y. Taniguchi, Y. Shioya, *Astrophys. J.* **547**, 146 (2001).
43. A. Toomre, J. Toomre, *Astrophys. J.* **178**, 623 (1972).
44. J. E. Barnes, *Nature* **344**, 379 (1990).
45. S. Lilly *et al.*, *Astrophys. J.* **500**, 75 (1998).
46. R. G. Abraham, M. R. Merrifield, R. S. Ellis, N. R. Tanvir, J. Brinchmann, *Mon. Not. R. Astron. Soc.* **308**, 569 (1999).
47. It is worth noting that the absence of bars cannot be due to morphological K-corrections [as suggested by P. B. Eskridge *et al.*, *Astron. J.* **119**, 536 (2000)], because it is seen to occur at redshifts in which the HST observations are well synchronized to blue optical wavelengths (i.e., at rest wavelengths where we are most familiar with the morphologies of nearby galaxies). Similarly, the effect cannot be due to a low signal-to-noise ratio in distant galaxy images, because simulations show that more than 90% of the strongly barred nearby galaxies in the Ohio State University Bright Spiral Galaxy Survey would remain obviously barred if seen at $z = 0.7$ in the HDF (S. van den Bergh *et al.*, in preparation).
48. B. Fuchs, S. von Linden, *Mon. Not. R. Astron. Soc.* **294**, 513 (1998).
49. B. Fuchs *et al.*, in press (available at http://xxx.lanl.gov/abs/astro-ph/0103375).
50. W. W. Morgan, *Publ. Astron. Soc. Pac.* **70**, 364 (1958).
51. _____, *Publ. Astron. Soc. Pac.* **71**, 394 (1959).
52. M. Doi, M. Fukugita, S. Okamura, *Mon. Not. R. Astron. Soc.* **264**, 832 (1993).
53. R. G. Abraham, F. Valdes, H. K. C. Yee, S. van den Bergh, *Astrophys. J.* **432**, 75 (1994).
54. C. Conselice, M. Bershady, A. Jangren, *Astrophys. J.* **529**, 886 (2000).
55. A. Naim, K. U. Ratnatunga, R. E. Griffiths, *Astrophys. J.* **476**, 510 (1997).
56. D. L. Block *et al.*, *Astron. Astrophys.* **371**, 393 (2001).
57. L. L. Cowie, A. Songaila, E. M. Hu, J. G. Cohen, *Astron. J.* **112**, 839 (1996).
58. C. C. Steidel, K. L. Adelberger, M. Giavalisco, M. Dickinson, M. Pettini, *Astrophys. J.* **519**, 1 (1999).
59. S. M. Pascarelle, R. A. Windhorst, S. P. Driver, E. J. Ostrander, W. C. Keel, *Astrophys. J.* **456**, L21 (1996).
60. R. Bouwens, T. Broadhurst, J. Silk, *Astrophys. J.* **506**, 579 (1998).
61. E. Hubble, *The Realm of the Nebulae* (Yale Univ. Press, New Haven, CT, 1936).
62. We thank R. Ellis, J. Brinchmann, M. Merrifield, R. Blandford, J. Cohen, and D. Hogg for many collaborative investigations into high-redshift galaxy morphology; J. Sellwood for sharing his thoughts on the formation and destruction of bars in galaxies; and R. Sword for helping to produce Fig. 1.