THE ASTROPHYSICAL JOURNAL, 435:L23–L26, 1994 November 1

NEW IMAGES OF THE DISTANT, RICH CLUSTER CL 0939+4713 WITH WFPC2

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Received 1994 May 17; accepted 1994 August 17

ABSTRACT

New images of the distant cluster of galaxies CL 0939+4713 at $z = 0.41$ have been taken with the WFPC2 on the *HST*. The images go deeper and show considerably more detail than the aberrated images from WFPC1. We confirm that for this cluster the Butcher-Oemler effect results from a surprisingly large population of late-type spiral and irregular galaxies. We also confirm and find further evidence for mergers and interactions that are a probable mechanism for the disappearance of this population by the present epoch. Based on the irregular forms of spirals in this cluster, we suggest that another mechanism may be the destabilization of disks in cluster galaxies as their halos are tidally distorted or removed through gravitational encounters.

The new data reveal many more faint objects, with much finer detail, around a quasar at $z = 2.055$ (Dressler et al. 1992). These data demonstrate the remarkable ability of *HST* to study the structural evolution of galaxies to very high redshifts.

Subject headings: galaxies: clusters of — galaxies: interactions

1. INTRODUCTION

Morphological classification of distant galaxies is a primary goal of imaging with the *Hubble Space Telescope* (*HST*). The discovery of spherical aberration of the primary mirror made this program more difficult by limiting the range in redshift and surface brightness over which distant galaxy images could be well resolved. Nevertheless, pictures taken with the Wide Field and Planetary Camera I (WFPC1) were found to be a vast improvement over any such data ever obtained with ground-based telescopes. Recently, Dressler et al. (1994, hereafter DOGB) showed typical results that were achieved with WFPC1: the resolution of the cluster CL 0939+4713 at $z = 0.41$ into elliptical S0, spiral, and irregular galaxies. These images provided, for the first time for galaxies at a lookback time of many billions of years, morphological data comparable to what can be achieved for relatively nearby clusters, which are observed essentially at the present epoch.

As part of the Early Release Observations (ERO) program for WFPC2, a camera with similar characteristics to WFPC1 but with its internal optics modified to correct the spherical aberration of *HST*, CL 0939+4713 was again targeted, in order to demonstrate by direct comparison the anticipated improvement and to assess quantitatively the gains achieved. In this *Letter* we show some results of this observation and discuss briefly some preliminary conclusions relevant to evolution of cluster galaxies.

2. DATA

As for the original WFPC1 observation, described in DOGB, the WFPC2 observation consisted of 10 single-orbit 2100 s exposures using the filter F702W. Due to lack of suitable guide stars during the brief ERO period, the field was rotated 90° relative to the earlier WFPC1 observation. This prevented the optimal positioning of the smaller-field-of-view PC on what was formerly chip 1 of the WFPC1, and the consequent loss of most of chip 2, which contained many interesting galaxies.

The observation was divided into two groups with a shift of 2″ S and 1″ E between the five frames taken on 1994 January 10 and those on 1994 January 12. The individual frames were processed using the standard STScI pipeline, which included bias and dark subtraction, and flat-fielding. The IRAF program IMALIGN was used to register the frames, and IMCOMBINE was used to combine each set of 10 images while eliminating most of the cosmic rays.

Cosmic rays appear to be a more substantial part of the signal of WFPC2 than WFPC1, but this is mostly due to the lower readout noise that enables a better detection of them in WFPC2. Also, there are a greater number of "hot pixels" in WFPC2, which are like single-pixel cosmic rays in appearance but fixed in location. Because our two sets of data were displaced, IMCOMBINE removed most of these hot pixels along with the true cosmic rays. This procedure produced a reasonably clean version of the final image, although it is likely that the image can be further improved by using an appropriate dark frame.

A. D. and A. O. met to examine the processed images in 1994 March. Using the object list compiled for DOGB, they reclassified the galaxies of that study from the new data, without referring to the earlier results. The revised Hubble system and a special class for mergers and interactions was again employed, as described in DOGB.

Reproductions of the full 80″ fields of the three Wide Field Camera (WFC) CCDs are shown in Figures 1–3 (Plates L11–L13). The Planetary Camera field, which sampled a relatively sparse area of the cluster, is not shown.

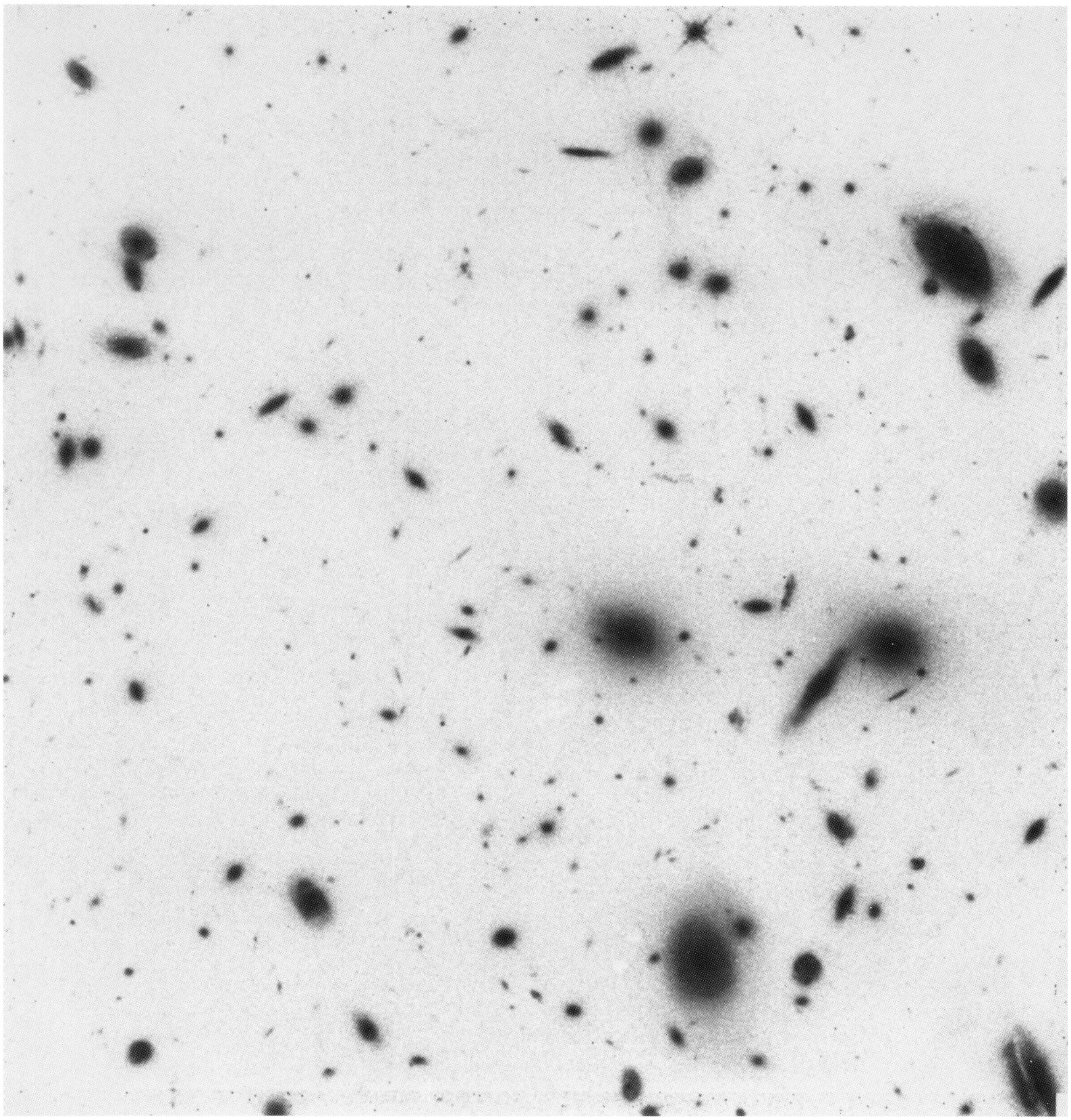

FIG. 1.—Chip 2, 820 × 820 pixels 0″.1 square covering the central regions of CL 0939+4713. North is up and east is to the left. Although the field includes the densest region of the cluster, many late-type, star-forming galaxies are visible, in contrast to present-epoch clusters of such high density. Many galaxy interactions and mergers are found in this region.

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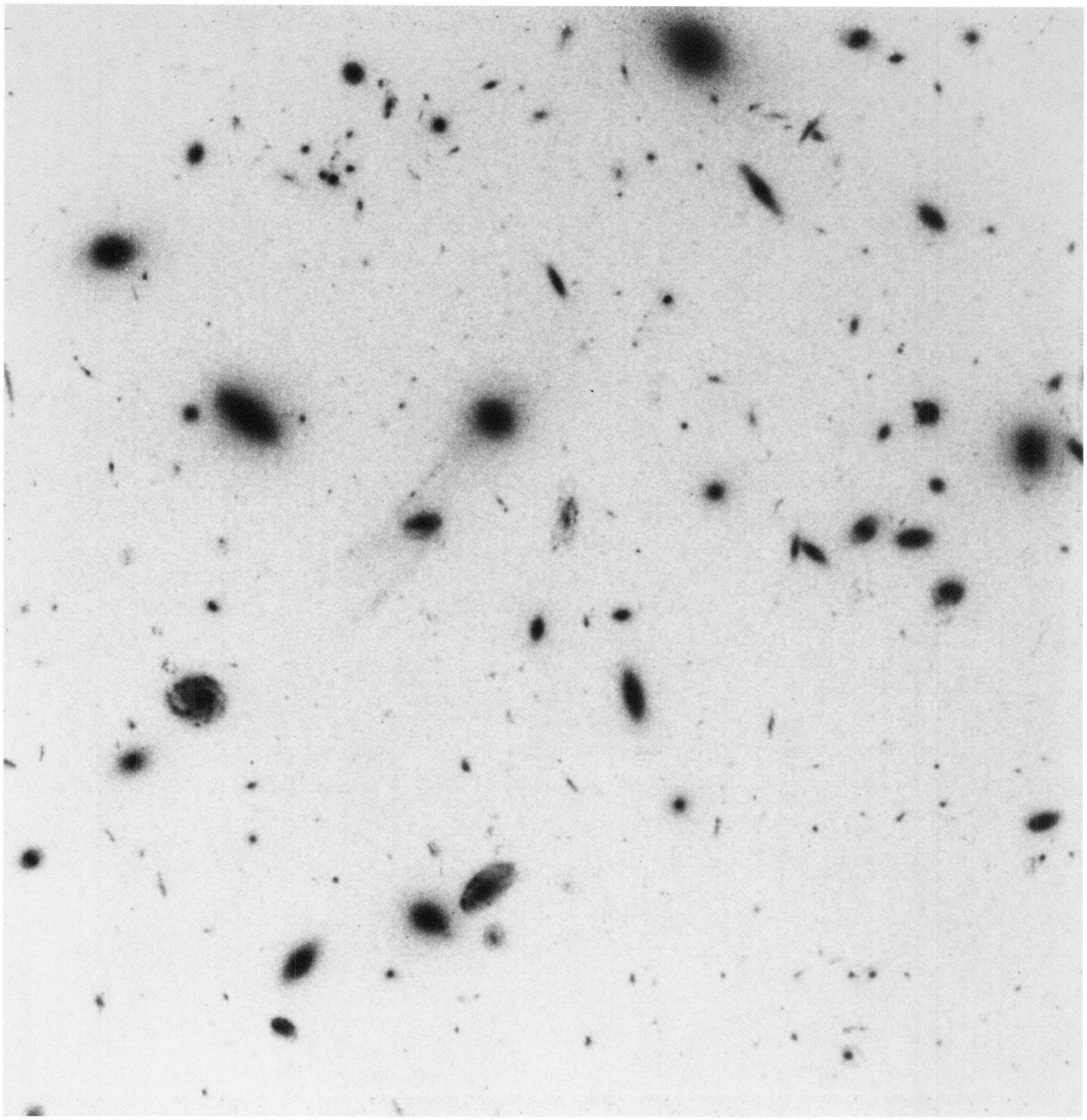

FIG. 2.—Same as Fig. 1, for the area immediately east of that field. A variety of late-type and interacting/merging galaxies are seen in this field as well, as well as the spray of faint objects running along the top of the picture, suggested by Dressler et al. (1992) to be associated with a quasar at $z = 2.055$.

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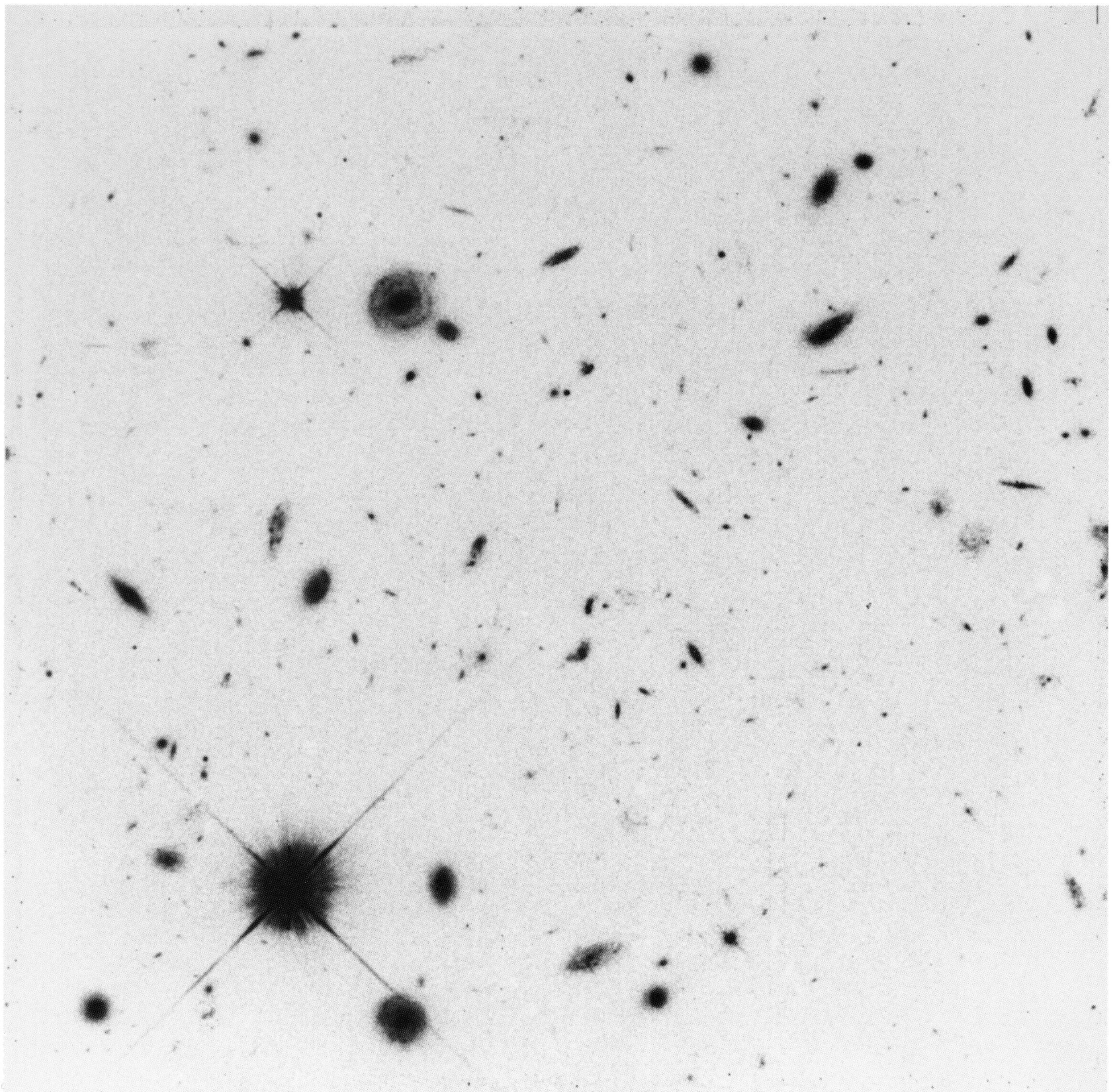

FIG. 3.—Same as Figs. 1 and 2, for the area southeast of the field in Fig. 1. Despite being only ~130″ (~600 kpc) from the cluster center, the population in this region is dominated by late-type spiral and irregular galaxies, a marked difference from any present-epoch cluster of this richness.

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3. RESULTS

3.1. *Morphological Classifications*

Our first result is shown in Figure 4, a comparison of morphological types for 112 galaxies in common between the 1992 data, which were WFPC1 images deconvolved using the Lucy-Richardson algorithm, and the WFPC2 images without image enhancement. The morphological types assigned by DOGB are largely confirmed by the new data, and it is interesting to note that the new types do not differ systematically from the old. For 84% of the sample galaxies the types agree to one class (i.e., the difference between an E and an S0, or an Sb and an Sc) or better: 46% were unchanged. However, the uncertainty of these types is clearly much improved over the WFC1 data; for example, the low-surface-brightness spiral structure of DG 234 (numbering system from Dressler & Gunn 1992), barely visible in the earlier data, is beautifully detailed in the new data. Several cases of suspected tidal interaction, particularly in close pairs, were found to be artifacts of the deconvolution process. A second advantage of the new data is the ability to classify much fainter galaxies—our sample here includes 28 galaxies with $r > 23.5$, compared to 9 with the earlier data, despite the 20% larger area of the earlier observations. Point sources to $r \sim 27.0$ and extended objects to $r \sim 26.5$ are clearly visible. Finally, and perhaps most importantly, the exposure time required to obtain such data has been dramatically reduced. As was expected from fact that only about 15% of the light in the WFPC1 fell within $r = 0\farcs1$, the WFPC2 can achieve a similar level of detail in less than 20% of the time. All of the science done in DOGB could have been done in a single orbit!

Aspects of this enhanced capability are shown in Figure 5, a color-magnitude-morphology diagram of DOGB for the new data. The principal features of the diagram are maintained, of course: the E and S0 sequence that defines the red edge of the diagram is well delineated, as well as the even progression to later-type spirals as colors become bluer. The new sample of faint objects includes galaxies of all types, although very late-type spirals predominate. This confirms, at least for this cluster, the important result of DOGB and Couch et al. (1994) that the Butcher-Oemler effect is due to a surprisingly large fraction of late-type galaxies. The remarkably high fraction of such galaxies is shown clearly in Figure 2, and even more strikingly in Figure 3. These fields look like *no* present-epoch, high-density cluster.

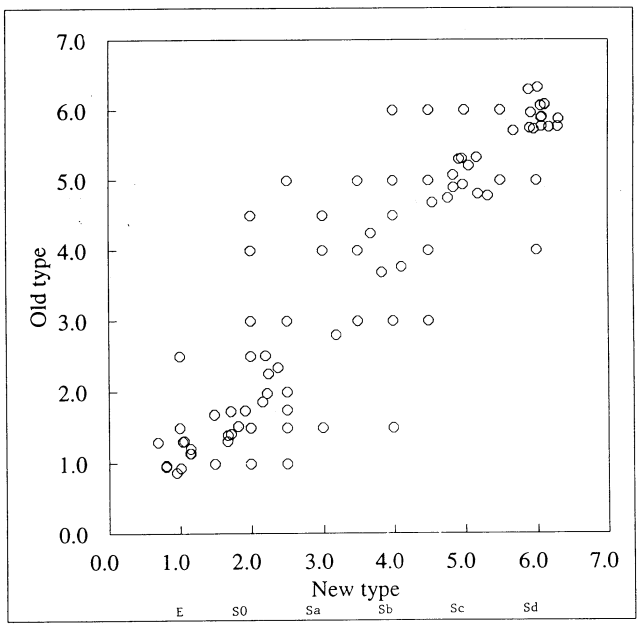

FIG. 4.—The morphological types assigned using deconvolved images from WFPC1 compared to types assigned using the WFPC2 data. For 112 galaxies in common, 84% of the assigned types agree to one class or better.

Another principal conclusion of DOGB was that mergers and interactions are an important feature of this cluster, occurring with a frequency perhaps an order of magnitude higher than low-redshift counterparts. The importance of such interactions to the Butcher-Oemler effect (1978, 1984) was first suggested by Thompson (1988) and investigated and supported by Lavery & Henry (1988) and Lavery, Pierce, & McClure (1992). Six of the eight galaxies classified as mergers in the WFPC1 data are common to the new data. Five are confirmed although, interestingly, one is found to be a late-type spiral and not a merger as previously thought. Although the spherical aberration and its attempted repair by deconvolution has affected many classifications at the level of a "one class" error, this complete misclassification highlights the difficulties of working with the earlier data.

However, the most significant change in the matter of mergers is the addition in the new data of five new cases. Two of these are fairly bright but redder ($g - r = 1.23$) than the earlier examples, and three are very faint, $r > 23$. These are just the cases one would expect to have missed previously. Evidence for a merger is likely to weaken as a system ages and presumably becomes redder; thus, finding redder examples lends support to the notion that at least some mergers evolve into red, quiescent E or S0 galaxies (Schweizer & Seitzer 1992). Consistent with this picture is the case of DG 434, for which the spectrum shows an old stellar population.

Fainter systems were, of course, more poorly restored by the deconvolution technique employed with the WFPC1 data. In the DOGB sample the absence of low-luminosity mergers was noted, with the expectation that such a selection effect might be at work rather than a true physical significance. Confirmation of this perhaps simplifies the task of understanding the merger process in clusters.

We have retained a strict criterion of strong tidal features for classification as "merger." More generally, we find that a substantial fraction—23 of the 181 newly classified galaxies—show some sign of interaction or disturbance by a near neighbor. We collect the best examples in Figure 6 (Plate L14). There is obvious tidal debris around the very bright galaxy DG 439, a galaxy that contains a remarkable dust-laden spiral pattern (although from its morphology and starburst spectrum it is certainly a merger product rather than a spiral galaxy). The distorted common envelope of DG 311 and its smaller companion DG 318 is a case of a strong interaction which may not lead to a merger. Tails are seen emanating from DG 451 (itself classified as a merger product and having a strong starburst spectrum) apparently interacting with DG 458 and DG 471, from which a straight jet of material points back to DG 458. A stream of material has apparently been pulled out of the spiral galaxy DG 380 in an encounter with the elliptical galaxy DG 398. More subtle examples are apparent on closer inspection of these images. It seems that navigating the environs of CL 0939+4713 some 4 billion years ago was a tricky business.

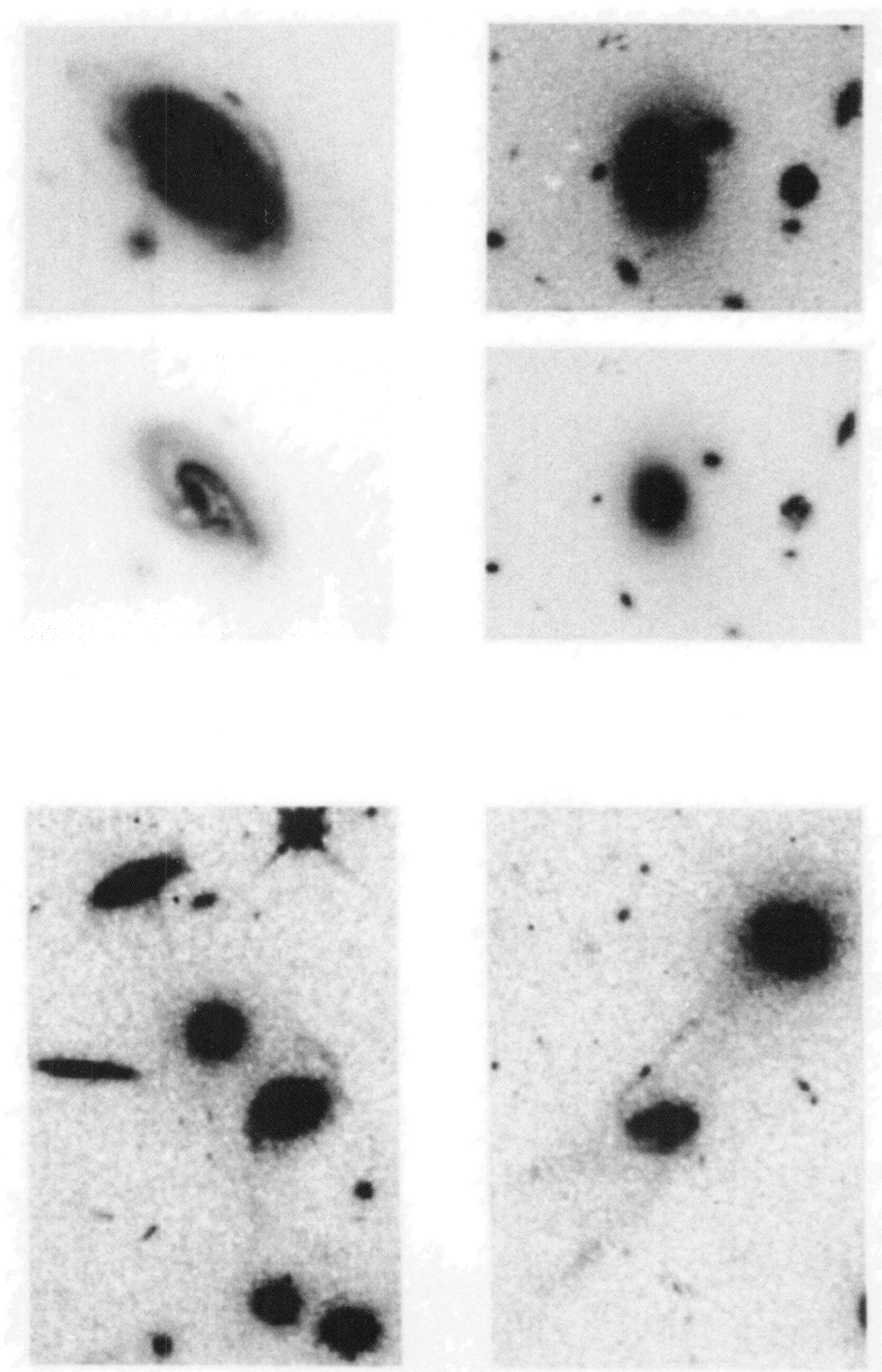

FIG. 6.—Examples of mergers or strong interactions. *Upper left:* DG 439, the result of a recent merger. *Upper right:* DG 311 and DG 318, in a common envelope. *Lower left:* DG 471, DG 458, and DG 451 (*top to bottom*), apparent participants in a multiple interaction. *Lower right:* material apparently drawn out from the spiral DG 380 in an encounter with the elliptical DG 398.

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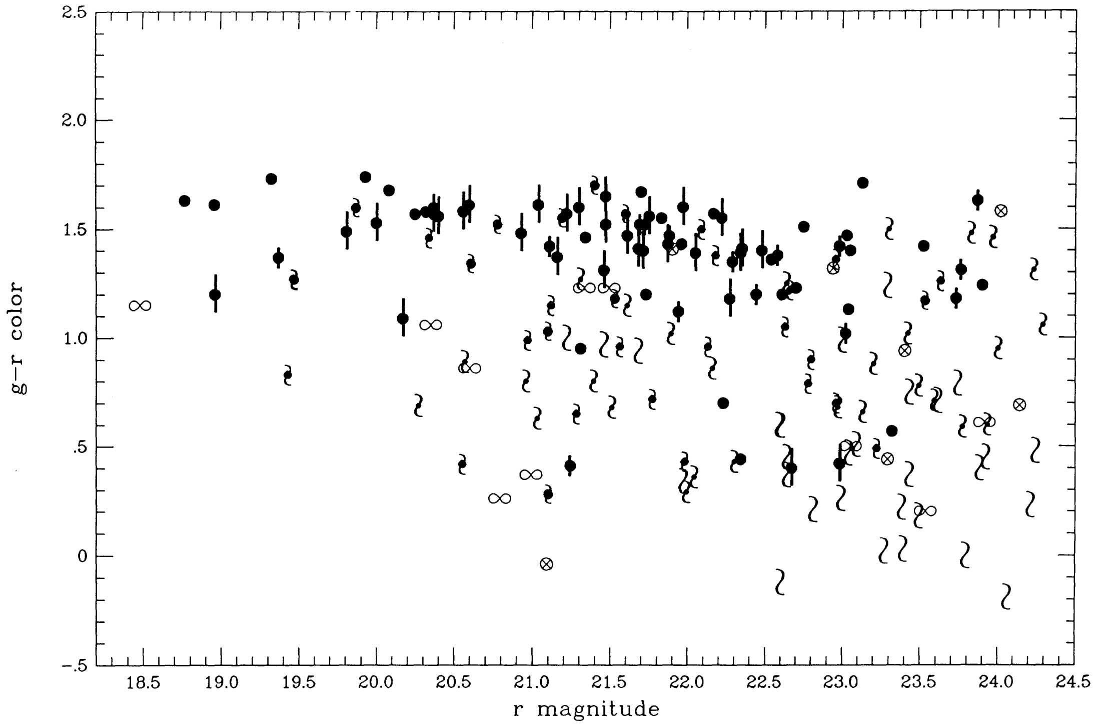

FIG. 5.—Color-magnitude diagram of the galaxies classified with the WFPC2 data. Morphological type is indicated by the following symbols: *filled circle*, E; *filled circle with straight line*, S0, *curved line with filled circle*, spiral, in order of decreasing circle size, Sa, Sb, Sc; *curved line*, Sd/Irr; *circled crosses*, compact (nonstellar but unclassifiable) objects; *double open circles*, mergers. The E and S0 galaxies form a reasonably tight sequence, but there are blue examples for which membership in the cluster is yet to be determined. As found by DOGB the majority of blue galaxies in this cluster, those responsible for the Butcher-Oemler effect, are late-type spirals. Eight merger candidates, covering the same range in color as the spirals and the entire luminosity range of the cluster, are found.

We return later to the question of the longevity of spiral galaxies in such circumstances.

The greater depth of these images makes obvious what was hinted at in earlier pictures of distant clusters taken with WFPC1: the profusion of faint, very late-type systems. We have, as yet, little information about them. For example, we can make only statistical arguments about their membership in the cluster, but it is clear from comparing number densities with fields taken as part of the Medium Deep Survey that many, if not most, of these must be associated with CL 0939+4713 (R. Griffiths and R. Ellis 1994, private communication). These are systems comparable in luminosity with the Magellanic Clouds. Systems this faint often have rather chaotic structures, but it will be interesting to see if the morphologies of these distant examples are even more extreme. Particularly striking is the number of edge-on systems, many of which have unusual kinks or bends compared to what is typically seen for present-epoch spiral disks. Possibly, some of these might be the results of gravitational lensing. Unlike clusters like A370 and CL 0024+1654, CL 0939+4713 contains no giant gravitation arcs. However, some tens of small arclike images can be seen in this image; they appear to be background sources lensed by individual galaxies rather than the overall cluster potential. As also noted by J. Ostriker (1944, private communication), the unprecedented resolution and limiting magnitude of this image means that such smaller lensing examples could not have been seen before. It is, therefore, possible that some of the very flat images thought to be late-type cluster galaxies are also representatives of this smaller-scale lensing phenomenon. The arcs in this and other clusters studied by our group will be the subject of a later paper.

3.2. *The Morphology of Putative Companions to the z = 2 Quasar*

Dressler et al. (1993) noted the presence of many faint, small, blue objects in the proximity of a very blue stellar source that was identified as a quasar with a redshift $z = 2.055$ by Dressler & Gunn (1992). The clustering of objects shows clearly in Figure 2 along the top edge, with the main concentration around the quasar left of center. This area, and an area to the west that Dressler et al. speculated contained associated objects, is shown enlarged in Figure 7 (Plate L15).

The new pictures strengthen in two ways the case for the association of these faint objects with each other, at least, if not with the quasar. First, additional, fainter objects are visible with the greater depth afforded to WFPC2. There are at least 24 apparently separate condensations within 10″ of the quasar, about twice the number seen previously. The clustering appears to be real, and the impression that these are objects at a similar distance, as judged by their size and surface brightness, is reinforced. Second, morphological information is now available for many of the brighter objects ($r \sim 23$–24). A few seem to be round, concentrated systems, but the majority are disklike (but very irregular) systems, easily distinguishable from the members of the foreground cluster.

With the deeper exposure these objects have not "grown together" to form a few larger systems, but rather have retained their identities as separate entities. (However, it is important to remember that, if at $z = 2.055$, these observations correspond to a mean rest-frame wavelength of 2300 Å, which would strongly favor hot spots of star formation over any older stellar component.) Even with the rather crude resolution available, these objects are not easily placed in present-epoch

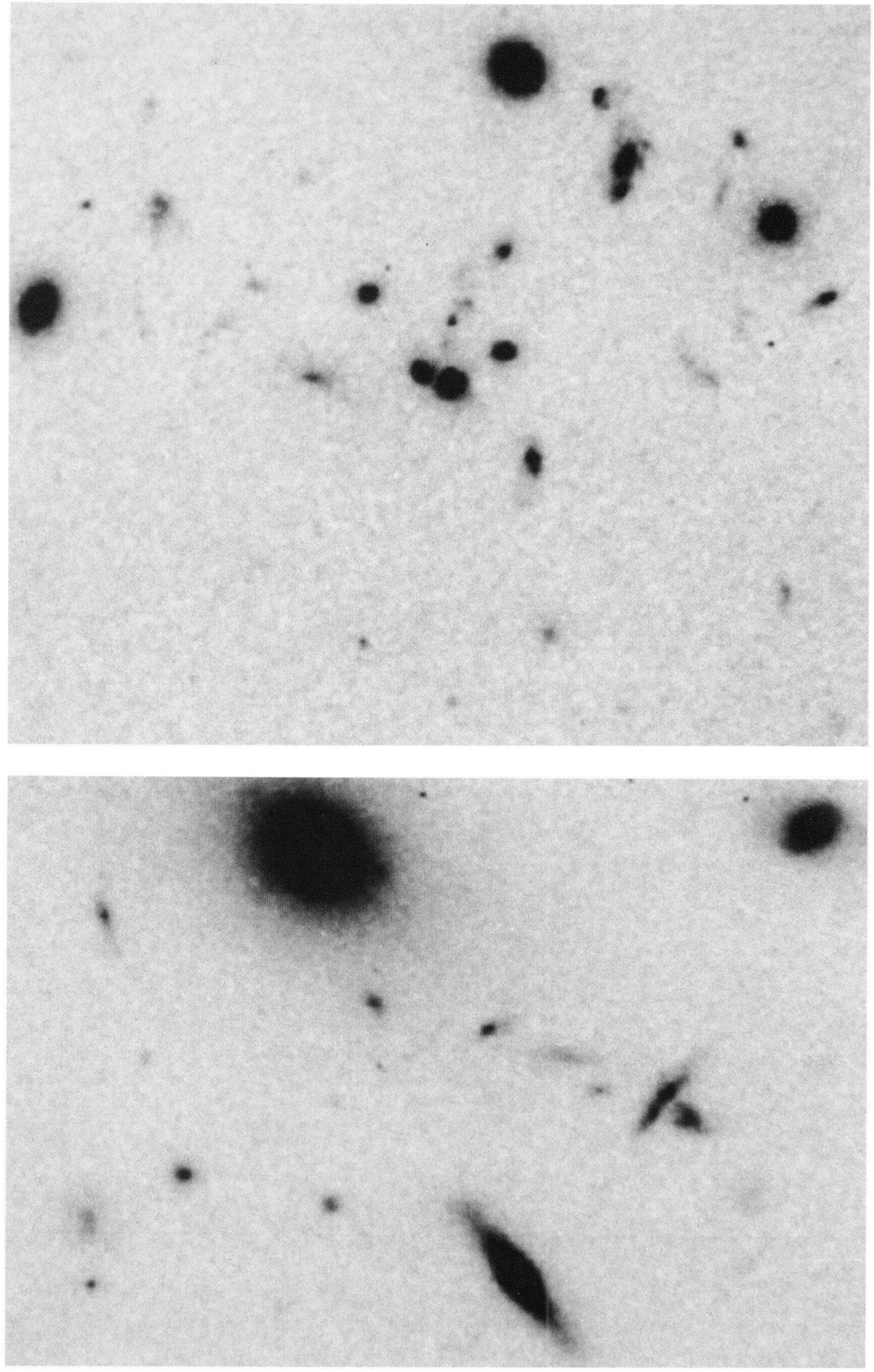

FIG. 7.—Enlargement of the region at the top of Fig. 2 showing the apparent clustering of faint objects suggested by Dressler et al. (1992) to be associated with a quasar at $z = 2.055$. North is at the left and east at the top. The brightest objects are members of CL 0939+4713. The top panel shows the quasar (brightest of the central three stellar objects) surrounded by some two dozen faint objects, $23 < r < 26$. The entire region is only 20″ across, so the area shown is only ~100 kpc. This and the size and irregularity of the objects suggests that these are galactic fragments seen in the process of building one or a few young galaxies. The bottom panel shows a region extending to the west of the quasar that could be part of the same cluster of very distant objects.

DRESSLER et al. (see 435, L25)

morphological classification systems, except to say that they resemble the latest-type irregular systems of the present epoch. This is further tantalizing evidence that these are indeed pregalactic systems that are in the process of forming what will become more recognizable galaxies, by both highly dissipative and nondissipative merger events. The largest and brightest of the companions, DG 452 (no. 2 in Dressler et al.), shows a spiral-like but distorted shape that includes two main condensations and several small streams of what must almost certainly be areas of intense star formation. The image of DG 450 (no. 8 in Dressler et al.) is so improved that its previously defined shape as a blobby triplet is now resolved as a warped disk with two intensity centers apparently interacting tidally, and perhaps about to merge with an irregular, half-shredded companion.

Although no redshift has been obtained that would confirm the association of any of these objects with the quasar, there should be doubt that the redshifts are considerably in excess of $z = 1$. One of us (A. D.) has looked at WFPC2 data for CL 1603+4313, observations taken in collaboration with the WFPC1 team as part of its GTO program. Despite the already large redshift of this cluster, $z = 0.90$, the brightest few dozen galaxies in this cluster bear little if any similarity to the objects surrounding the quasar in the CL 0939+4713 field. From colors, morphology, and size, it would seem hard to escape the conclusion that these are objects at much higher redshift, and quite probably at $z = 2.055$.

As remarkable as these images of systems at high redshift are, they point up the need for longer exposures and higher resolution. At 7000 Å *HST* has a potential resolution of about 0\".07 FWHM, but the WFC severely undersamples this with 0\".1 pixels. Substepping with the 0\".04 pixels of the PC would dramatically increase the detail in these very high redshift systems, though it is apparent that the exposure times will be lengthy. The indications from these early pictures are that galaxies with redshifts $z \lesssim 1$ are definitely accessible with *HST*, but that one can plan on exploring much higher redshifts where observing galaxy formation is a real possibility, if future time allocation committees can be persuaded to commit the very substantial resources that will be necessary.

4. DISK DESTABILIZATION: ANOTHER MECHANISM OF DESTROYING THE SPIRALS IN HIGH-REDSHIFT CLUSTERS?

There is no doubt that much can be learned in the coming years about the development of structure in galaxies through *HST* observations of high-redshift examples, both inside and outside of clusters. We have already confirmed the presence of large numbers of late-type spiral and irregular galaxies at $z \sim 0.4$ that have for the present part disappeared from present-epoch clusters. It is this disappearance of late-types that is now the central mystery in the effect first noted by Butcher & Oemler.

We have been tempted to wonder if the disappearance of spirals might be related to the general tendency we have noted for late-type galaxies in CL 0939+4713 to have an irregular appearance—even the most "normal" spirals seem to have one odd feature or another. In Figure 8 (Plate L16) we show the 24 brightest galaxies classified as spirals in this image, $19.9 < r < 22.3$. Few remind us of the familiar types we find in the Hubble Atlas. Of course, this impression is difficult to quantify, and could be misleading because our comparison is with the Hubble Atlas, which is meant to be illustrative rather than representative.

We also show in Figure 8 seven examples of mergers and one strong tidal interaction. Mergers and tidal interactions are certainly processes that help destroy or suppress (by fading) late-type galaxies, but their efficiency is limited by the number of galaxy-galaxy interactions. A more global mechanism, one that would affect any infalling spiral—like the interaction with the intracluster gas—would have more general impact.

The "irregularity" of even fairly normal spirals, and the abundance of small, disky but disorganized systems—even when there is no obvious galaxy-galaxy interaction—suggests that another mechanism might be at work. We recall the argument made by Ostriker & Peebles (1973) that disk galaxies require substantial halos to avoid various dynamical instabilities that could heat and destroy a thin disk. Might we be seeing the effect of disk galaxies losing too much of their dark-matter halos as they plunge into the dense cluster environment? Even if the halos are not altogether disrupted, one might imagine that the traverse through a rapidly varying cluster potential might induce distortions and oscillations in a galaxy's halo that might have devastating effect on a fragile disk. Whether by disruption or the rapid conversion of gas to stars, the consequences for a spiral should be important to its evolution. It would be interesting to investigate the ramifications of such destabilization on the regularity of the spiral pattern, the warping of the disk, and, over the long term, the survival of the galaxy as a star-forming spiral.

The authors gratefully acknowledge the efforts of all those who labored so long and so successfully to restore the *Hubble Space Telescope* to its planned performance. We are in their debt. Chief among them is Bob Williams, whose vigorous support of this particular observation was decisive.

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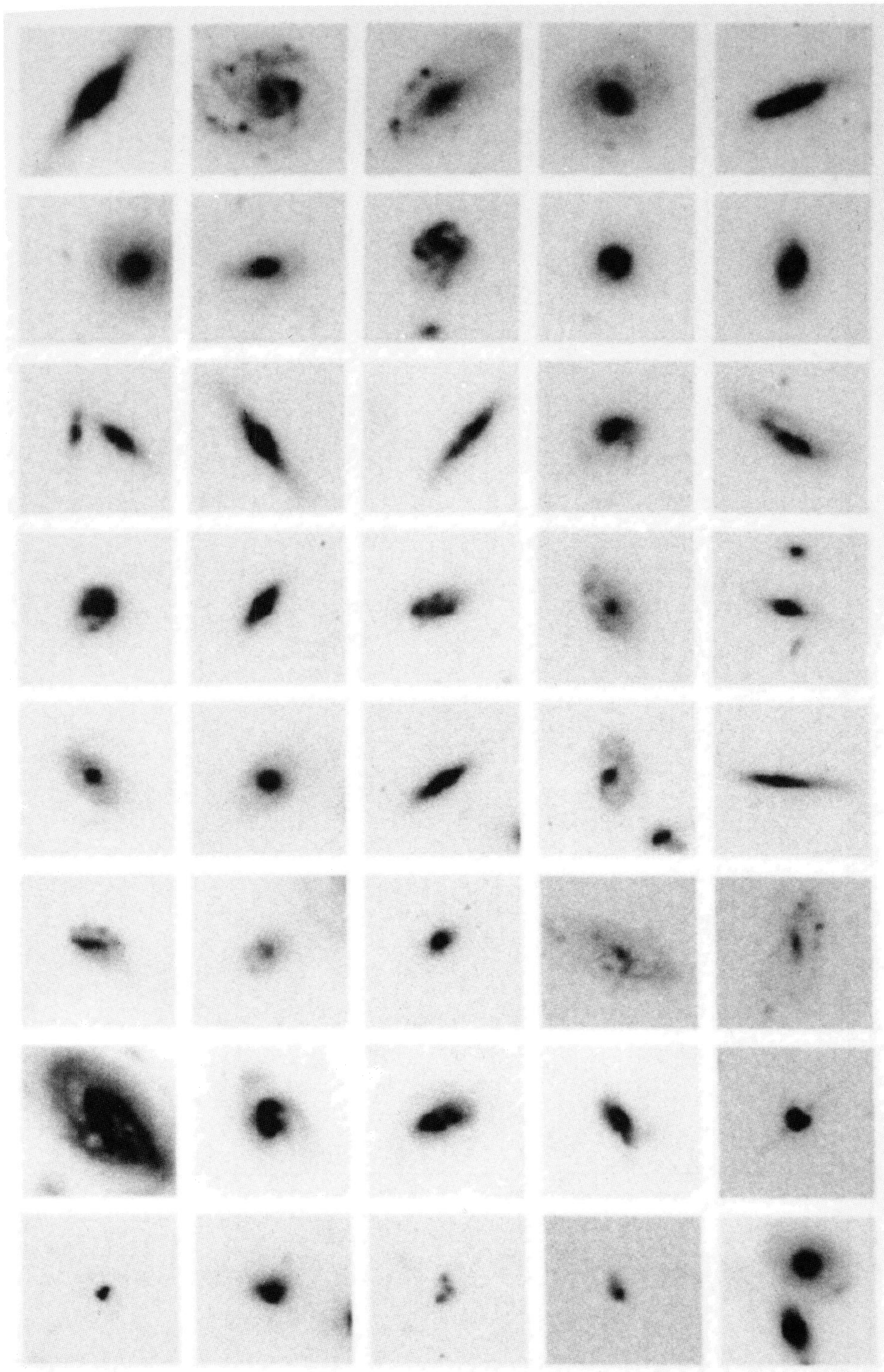

FIG. 8.—Montage of galaxies from CL 0939+4713. The top five rows are the brightest spirals, covering $19.9 < r < 22.3$. Many, if not most, of the spirals appear more irregular than the common examples of present-epoch Hubble types. The bottom two rows show examples of mergers, judged by evident tidal features. The bottom right shows two galaxies (DG 431 and DG 436) separated by only 1″ where no tidal interaction is apparent, suggesting that proximity alone is not a reliable measure ot interaction.

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