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IS THERE A DEFICIT OF S0 GALAXIES AT INTERMEDIATE REDSHIFT?[1]

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ABSTRACT

Two contradictory results on the evolution of SO galaxies now exist in the recent literature: either S0's are old ($z_{\rm formation} > 2$) and are evolving passively or most of them form at $z < 0.5$, as implied by the deficit of S0's in intermediate-redshift ($z \sim 0.5$) clusters. The resolution of this controversy may be that the apparent deficit of S0's has been derived from a quantity—the E-to-S0 ratio—that is prone to morphological classification errors. Once all sources of error are taken into account, the E-to-S0 ratios of clusters at different redshifts are fully compatible, and no additional creation of S0's at $z < 0.5$ is required by the data. Furthermore, there is no deficit at all of S0's in the intermediate-redshift cluster for which we have morphological types of very high quality and thus derive an E-to-S0 ratio with a small error.

Subject headings: galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: statistics

1. INTRODUCTION

The S0 class is often considered a class of transition between elliptical and spiral galaxies (see, for example, Hubble 1936; but see van den Bergh 1976 for an opposite opinion). Evidence for the evolution of the S0's was sought measuring a heterogeneity of this class, a heterogeneity that suggests a variety of evolutionary paths that end in an S0 galaxy. Color and color dispersion of S0's (Sandage & Visvanathan 1978; Bothun & Gregg 1990; Bower, Lucey, & Ellis 1992), segregation in clusters (Oemler 1974; Dressler 1980b), location in the fundamental plane (Saglia, Bender, & Dressler 1993), geometrical properties (Michard 1994), the presence of unusual features such as shells and ripples (Schweizer et al. 1990)—all these factors give contradictory indications on the origin of S0 galaxies.

Recently, the advent of the *Hubble Space Telescope* has permitted a major breakthrough: its superb angular resolution allows the morphological classification of distant galaxies and, therefore, the comparison of the properties of the morphological types at quite different redshift, i.e., at different look-back times. The evolutionary history of the morphological types need no longer be indirectly inferred by the relics it leaves in the galaxy properties, but now can be caught in the act.

Two recent papers by the MORPHS collaboration (Smail et al. 1997; Dressler et al. 1997, herafter collectively MORPHS) present evidence for the evolution of the S0 class between $z \sim 0.5$ and $z \sim 0$. MORPHS noted that in intermediate-redshift ($z \sim 0.5$) clusters there is a deficit of S0's with respect to nearby clusters.

This situation is quite puzzling: intermediate-redshift lenticular galaxies are red, with little scatter in color, and therefore are thought to be as old as elliptical galaxies ($z_{\rm formation} > 2$; Ellis et al. 1997; Andreon, Davoust, & Heim 1997). Nevertheless, their number seems very low, so that many of them must be "created" in order to reach the population of S0's in nearby clusters (Dressler et al. 1997). Furthermore, Coma lenticular galaxies, and possibly others, are too old and homogeneous in their properties to be formed at $z < 0.5$ (Bower et al. 1992; Andreon 1996). Therefore, S0's in clusters should have $z_{\rm formation} < 0.5$ and $z_{\rm formation} > 2$ at the same time.

The deficit of S0 galaxies is not shared by all clusters. In one of the three clusters at $z \sim 0.3$ studied by Couch et al. (1998), the S0 fraction is quite similar to that found in nearby clusters, whereas in the two others it is intermediate between nearby and $z \sim 0.5$ clusters. In the cluster Cl 0939+4713 ($z \sim 0.4$) S0's are as frequent as in the nearby Coma Cluster (Andreon et al. 1997a), a result that would imply no evolution with time for the S0 population. The situation is striking for this cluster, since Dressler et al. (1997) and Andreon et al. (1997a) find opposite results for the same sample of galaxies and from very similar analyses of the same WFPC2 post-COSTAR images of the *Hubble Space Telescope.*

Therefore, further analysis is useful in order to understand these discrepancies.

2. A DEEPER LOOK AT THE DATA

Since the spiral population in clusters evolves with redshift (Dressler et al. 1994; Oemler, Dressler, & Butcher 1997; Dressler et al. 1997; Andreon et al. 1997a), the evolution of S0 galaxies has to be inferred from the variation of the ratio between the E and S0 populations.

The typical composition of nearby clusters, as computed by Dressler et al. (1997) for a large sample of galaxies drawn from a catalog with undefined completeness, is quite similar to the composition of the nearby Coma Cluster computed by Andreon et al. (1997a): E:S0:S = 25:42:31. The latter composition has been computed adopting the same absolute magnitude limit and the same rest-frame passband used for intermediate-redshift galaxies.

Intermediate-redshift clusters have a typical composition of E:S0:S = 37:19:44 for the $\sim$600 galaxy sample of Dressler et al. (1997), whereas Andreon et al. (1997a) find E:S0:S = 15:34:43 for a smaller sample of $\sim$70 galaxies in Cl 0939+4713. The two E-to-S0 population ratios at $z \sim 0.4$ computed from these cluster compositions are statistically different at the 99.999% confidence level. Therefore, the difference between the two E-to-S0 ratios is not due to small-number statistics. Dressler et al. (1997) estimate the E-to-S0 ratios of intermediate-redshift clusters and of

[1] Based on observations obtained with the NASAESA *Hubble Space Telescope.*

nearby clusters as statistically different, while Andreon et al. (1997a) find them equal. Therefore, the disagreement between the two works and the puzzle of the deficit of S0 galaxies in intermediate-redshift clusters is not due to differences in the zero-redshift samples or to small-number statistics. We now need to analyze the possible existence of other sources of error in the E-to-S0 ratio.

A possible source comes from morphological misclassifications. The error (scatter) on the MORPHS morphological types of intermediate-redshift galaxies is quantified by Smail et al. (1997) in their Figure 1. About 20% of all galaxies in the magnitude range of interest (brighter than the classification limit adopted in estimating the E-to-S0 ratio) have morphological estimates that differ, from morphologist to morphologist, by more than one class in the revised Hubble scheme, i.e., the difference between an E and a S0 or between an S0 and an Sa. The error on the morphological types claimed by MORPHS is not small enough to exclude the possibility that the S0 population is the same at $z \sim 0.5$ and in the local universe. In fact, an error of one morphological bin for only 20% of the galaxies (for instance, if one moves 10% of all the objects from E to S0 and another 10% from S to S0) would give the zero-redshift ratio. Even smaller errors on the morphological classification are sufficient to explain the values and the scatter of the E-to-S0 ratios found by Couch et al. (1998) in three clusters at $z \sim 0.31$.

If, at the difference of MORPHS, we take into account the error on the morphological type, which is the dominant factor, in the computation of the error on the E-to-S0 ratio, then the MORPHS E-to-S0 ratios at different redshifts are equal within the errors. Therefore, we can conservatively state that there is, up to now, no evidence for a deficit of S0's in intermediate-redshift clusters. The evolution of the cluster S0 population is not required by MORPHS data (or better, by the present analysis of the data).

Systematic errors are even more dangerous. Here, as well explained by MORPHS, we are interested in differential morphological errors, i.e., in possible factors that render the morphological classification dependent on redshift. Classification errors equally affecting nearby and intermediate-redshift clusters (e.g., the misclassification of face-on lenticular galaxies as elliptical galaxies; Capaccioli 1987) do not affect the ratio of E and S0 populations, since they cancel out in the comparison as long as the fraction of misclassified galaxies is the same at all redshifts. As shown in Andreon et al. (1997a) and Dressler et al. (1997), images of intermediate-redshift clusters from the space very closely resemble ground-based images of nearby clusters in terms of rest-frame deepness, resolution, and sampled passband. This seems to exclude an important differential effect on the determination of the morphological composition because of the different nature of the images. However, given the subjective nature of the morphological classification, this is not fully guaranteed.

In order to investigate the possible existence of systematic errors in the morphological classification, we compare the MORPHS morphological scheme, based on the resemblance of galaxies to standards, with a classification method that relies on the detection of structural components (such as disk, bar, spiral arm, bulge, or halo). Two clusters are available for this exercise: the nearby Coma Cluster (whose Hubble types are listed in Andreon et al. 1996; Andreon, Davoust, & Poulain 1997b) and the intermediate-redshift Cl 0939+4713 cluster (whose Hubble types are listed in Andreon et al. 1997a).

At this stage, one has to comment upon the definition of the E and S0 types. According to de Vaucouleurs (1959) and Sandage (1961), the segregation between E and S0 types is based upon the examination of the surface brightness profiles along the major axis of the galaxy. The presence of a disk gives a characteristic bump above the radial profile, typical of pure spheroidal galaxies. We classify a galaxy as S0 if it does not have spiral arms or irregular isophotes and if it presents a bump in its major-axis surface brightness profile, which is absent or at most hinted at in the minor-axis profile (see, for example, DG 250, DG 303, or DG 310 in Fig. 1), in the spirit of the Hubble definition for this class (see Andreon & Davoust 1997 for details). MORPHS discriminate between E and S0 according to their resemblance to their respective morphological standards.

The morphological type of Coma galaxies provided by Dressler (1980a; used by MORPHS) and Andreon et al. (1996, 1997b) agree well within the usual 20% of scatter (Andreon & Davoust 1997), and the E-to-S0 ratios computed from these data are very similar, as expected, given the agreement between these authors on the morphological composition at zero redshift. For certain or likely members of the Cl 0939+4713 cluster, the structural and traditional morphological types show a similar scatter: 23% of galaxies have different types (15 galaxies out of 65) when they are binned in the usual three classes (E, S0, and S), while peculiar galaxies are neglected. The disagreement drops to 18% if we do not count as truly discrepant those galaxies whose MORPHS type is uncertain between the structural type and another type. There is, therefore, the same agreement between structural and traditional types (at most 23% of them differ) as among the types estimated by traditional morphologists (20% of them differ), thus showing that structural types are not worse than traditional ones.

However, Cl 0939+4713 is S0-rich using structural types, whereas it is S0-poor using traditional types. Since the existence of a deficit of S0's in Cl 0939+4713 strongly depends on which classification scheme is used, and both schemes are equally good, we can safely conclude that the claimed deficit of S0's in this intermediate-redshift cluster has been derived from a quantity, the E-to-S0 ratio, that is prone to classification errors.

Let us now move to a detailed comparison of galaxies with discrepant types. Out of 15 galaxies with discrepant structural and traditional morphological types in Cl 0939+4713, 13 are classified as S0's in Andreon et al. (1997a) and as ellipticals (7) or spirals (6) by MORPHS.

Figure 1 shows the major- and minor-axis surface brightness profile of the seven galaxies in Cl 0939+4713, whose structural type is S0 but which are classified as ellipticals by MORPHS. The curvature of the major-axis surface brightness profile and the linearity of the minor-axis profile of three of them (DG 250, DG 303, DG 310) are unquestionable. These features are less evident, but still present, in DG 314, DG 443, and DG 457. In DG 302, the bump can be hinted at at $r^{1/4} \sim 0''.75$. S0's in Coma and in Cl 0939+4713, as classified by means of their structural type, show similar ellipticity profiles and cos (4θ) deviations of the isophotes from perfect elliptical shape (see Andreon et al. 1997a for details). Therefore, these galaxies are much more likely to be lenticular galaxies than elliptical galaxies. Similar classification problems are also mentioned by the

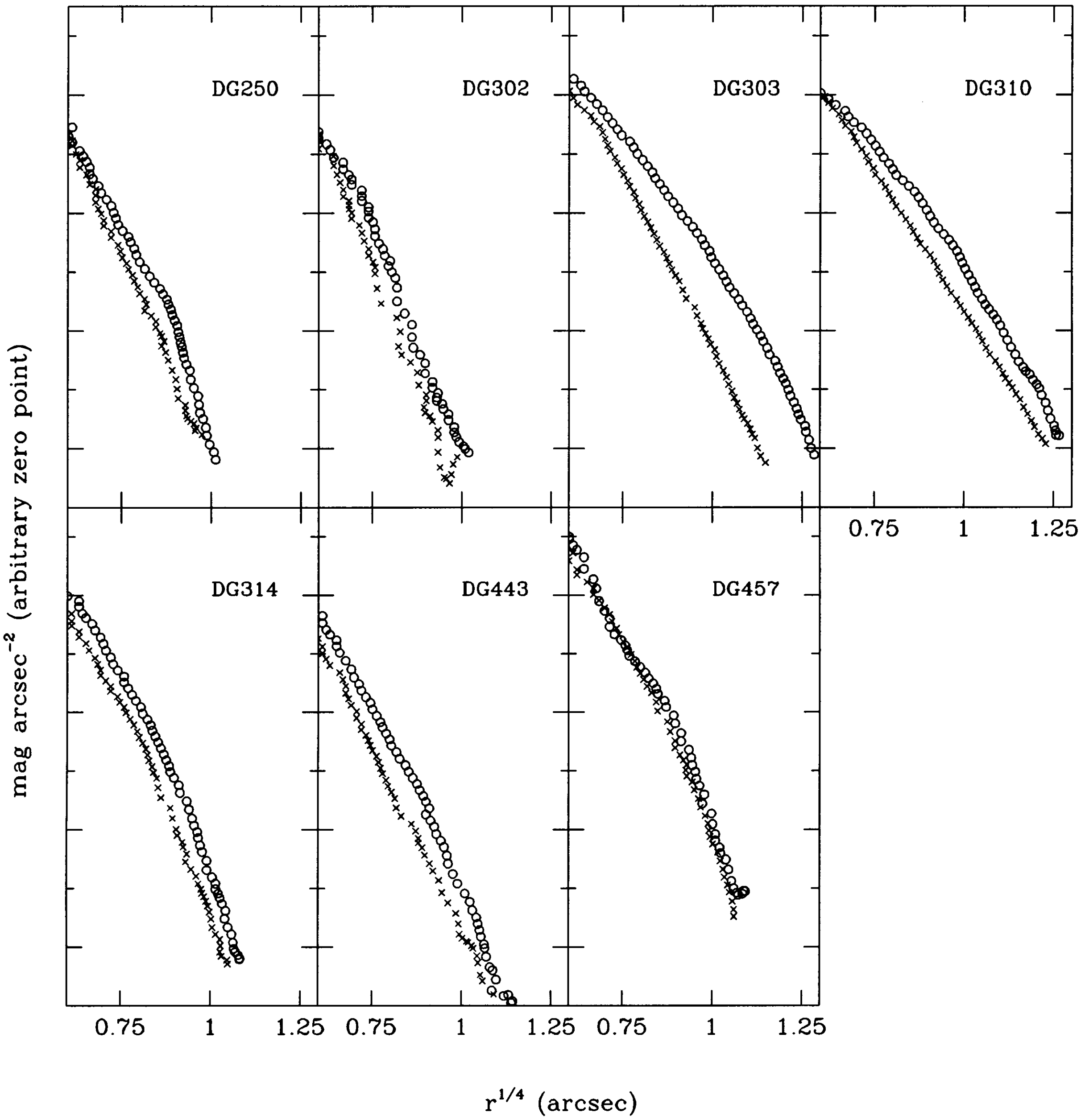

FIG. 1.—Major-axis (*circles*) and minor-axis (*crosses*) surface brightness profiles for galaxies whose structural type is S0 but traditional type is E

two authors of the MORPHS papers (Couch et al. 1998).

Figure 2 shows the images of the six galaxies whose structural type is S0, although their traditional type is S. The MORPHS types for these galaxies are S0/a, Sb, and Sbc (two cases each). Any spiral arm or irregularity, which characterizes them as spirals, is visible in their images. If spiral arms were present, we would see them. In fact, Figure 3 shows that all other early-type spirals, i.e., Sa and Sbc (there are no Sab or Sb types in the studied sample), as classified by MORPHS in Cl 0939+4713, show spiral arms, thus showing that the signature we are looking for is visible in the available images. The images that we compare contain galaxies of similar magnitudes. They are also part of the same image of Cl 0939+4713, they are shown with the same cuts, and they are therefore fully comparable. To summarize, these six galaxies with discrepant types in the two works are correctly not classified as spiral by Andreon et al. (1997a), since spiral arms, when present, are visible in the available image.

In conclusion, in individual galaxies for which structural and traditional types differ, the structural type gives a better description of the galaxy appearance, avoiding the classification of galaxies without spiral arms as spirals and of galaxies with a bulge and a disk as ellipticals. To give larger weight to these types, as justified in previous paragraphs, means to find no deficit at all for S0's in the intermediate-redshift cluster Cl 0939+4713. For this cluster, any S0's should be "created" to reach the S0 population of nearby clusters.

3. DISCUSSION AND CONCLUSIONS

Smail et al. (1997) and Dressler et al. (1997) are aware that the claimed deficit of S0's in intermediate-redshift clusters holds only in the absence of redshift-dependent errors in their morphological classification. For quantifying systematic errors, they compared the ellipticity distribution of the

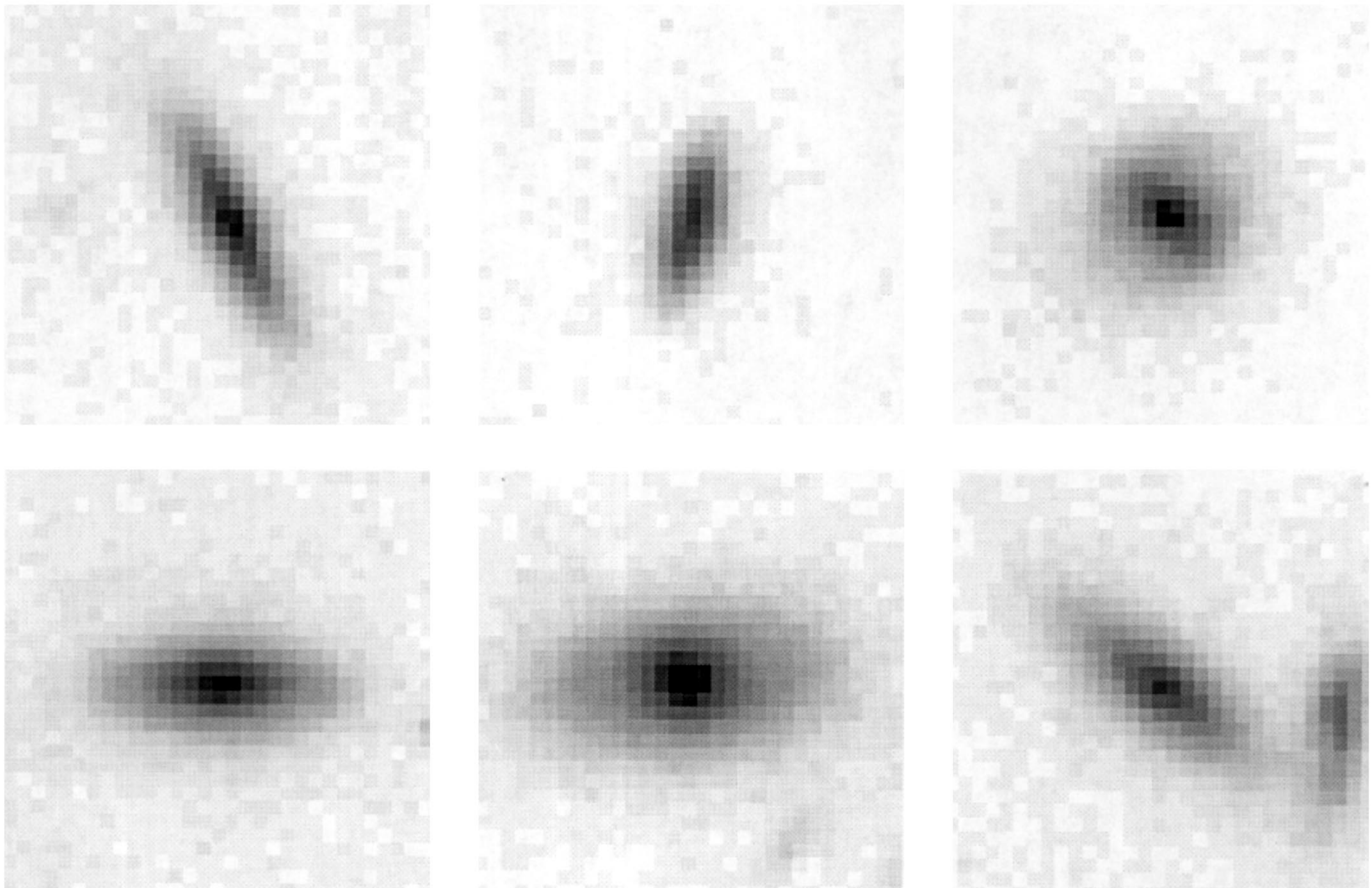

FIG. 2.—Mosaic of the F702W images of the galaxies whose structural type is S0 and traditional type is S.

morphological types at intermediate redshift and of the nearby universe. For nearby samples, they used the Revised Shapley-Ames Catalog (Sandage, Freeman, & Stokes 1970) and a magnitude-complete sample of galaxies in Coma (Andreon et al. 1996), the latter being preferable (Smail et al. 1997) because the ellipticities were measured approximately at the same isophote as the compared sample. MORPHS find that the ellipticity distribution of intermediate-redshift and nearby Hubble classes are compatible and conclude that, in spite of the 20% scatter in the morphological types present in their sample, their classification is equally good and has no bias with redshift. However, this comparison is intended to look for redshift-dependent trends in the morphological classification by means of an indirect quantity, the ellipticity distribution of the Hubble types, and does not directly test the quantity of interest, the redshift dependence of the morphological classification, as we do in our comparisons for Coma and Cl $0939+4713$ morphological types.

To summarize, we have shown that the E-to-S0 ratios of nearby and intermediate-redshift clusters are equal within the errors once the error on the morphological type, which is the dominant term, is taken into account. The comparison of equally good morphological types measured by means of independent morphological schemes of the galaxies in Cl $0939+4713$ confirms for this cluster that the claimed deficit of S0's is the result of having measured it by a quantity too prone to morphological errors. Therefore the evolution of the S0 fraction from $z \sim 0.5$ to the present time is no longer required by the MORPHS data (or, better, by the present analysis of the data), thus solving the puzzle of the old age of the S0's and their absence at $z \sim 0.5$. Furthermore, there is no deficit at all of S0's in the intermediate-redshift cluster, for which we have very high-quality morphological types and thus derive an E-to-S0 ratio with small error.

However, our conclusion should not be overinterpreted. First of all, we have not shown the absence of an evolution in all the properties of early-type galaxies, from $z \sim 0.5$ to the present time. We have just shown that there is no evidence for an evolution of the relative fraction of early-type galaxies. Strictly speaking, the constancy of the E-to-S0 ratio does not exclude morphological changes of individual galaxies between these two classes, or from spiral to elliptical or S0 classes, but just gives some constraints on the evolution of the two populations. Individual galaxies can change their morphological type while keeping the E-to-S0 ratio constant, provided that the same number of ellipticals become S0's and vice versa, or, when spiral galaxies are involved, that spirals become ellipticals or S0's with the right frequency. Furthermore, a 20% of scatter (error) in the morphological type, claimed both by MORPHS and by ourselves (this work and Andreon & Davoust 1997), is not a negative judgment of the MORPHS work, since it is usual in all morphological studies—so usual that better agreements are suspicious (Andreon & Davoust 1997). The presence of systematic errors in the morphological classifications does not make MORPHS types useless, since they are still useful for studying quantities less affected by systematic errors. A better morphological type for all intermediate galaxies, such as a structural one, would need a 60

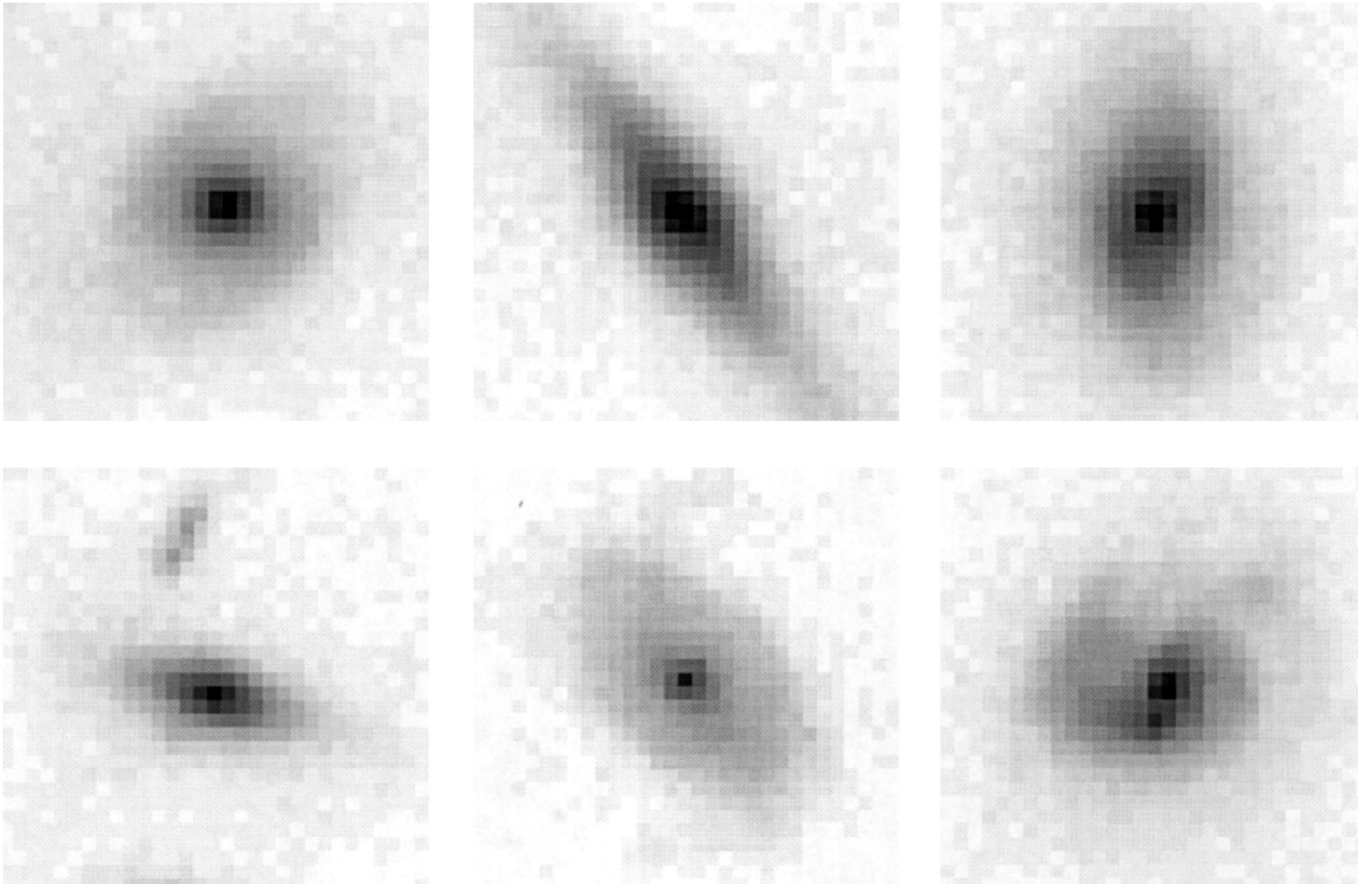

FIG. 3.—Mosaic of the F702W images of the galaxies whose structural and traditional type is S. Images are shown with the same cuts and look-up table as in the previous figure and have been extracted from the same image.

times larger effort (Andreon & Davoust 1997) and thus is out of our present capabilities.

Recently, van Dokkum et al. (1998) found that, at large clustercentric radii ($R > 0.7\ h_{50}^{-1}$ Mpc) of the intermediate-redshift cluster Cl 1358+62, S0's are heterogeneous in color and therefore experienced star formation very recently, conclusions opposite to those from previous works focused on the central regions of other intermediate-redshift clusters (Ellis et al. 1997; Andreon et al. 1997a). They suggest that S0's evolve primarily in the transition region between the cluster and the field, giving support to the MORPHS finding that S0's are still forming at intermediate redshift. However, van Dokkum et al. (1998) choose to classify as spiral only star-forming galaxies, leaving spirals with faint smooth spiral structure in the S0 class (see their § 2.3.1). This is confirmed by the inspection of their black-and-white prints presented in their Figure 3: at least 25% of all galaxies that van Dokkum et al. classify as S0's are spirals, according to MORPHS or our morphological scheme. All these galaxies present smooth spiral arms (or irregular isophotes) and look like the spirals in Cl 0939+4713 shown in Figure 3 or the Coma spirals. Therefore, van Dokkum et al. (1998) adopt a classification scheme different from the one adopted by other researchers. The shape of the azimuthal-averaged surface brightness profile measured by van Dokkum et al. (1998) does not discriminate S0's from early-type spirals, since the difference between the two types is given by the smooth spiral arms whose contribution to the radial surface brightness profile is negligible. Their conclusion about the evolutive nature of S0's is therefore relative to their S0 class and not to the Hubble S0 class. A reclassification of van Dokkum et al.'s S0's in the Hubble scheme would help in understanding which part of the heterogeneity of their S0 class is due to the pollution by early-type spirals and which part is intrinsic and suggestive of recent formation. At small clustercentric radii, where the misclassification is likely low because of the morphological segregation, van Dokkum et al.'s S0's are a homogeneous old population of galaxies, as in all the other studied clusters, both in the nearby universe and at intermediate redshift.

As a final remark, we stress that the morphological type is a quantity that needs to be calibrated and given with its error, as is usual for all other physical quantities. We reiterate the need for using a classification method that keeps morphological-type errors and systematic differences from the standard scale to a minimum, adopting the Hubble sequence as a standard reference.

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