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A CLUSTER OF NASCENT GALAXIES AT $z = 2$?

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ABSTRACT

On a 6 hr Wide Field Camera exposure with the *Hubble Space Telescope* of the rich cluster CL 0939+4713, we have identified an apparent cluster of ~30 faint, extended objects with magnitudes $22 < r < 25$. The objects are typically 1″ in size with bright central regions only a few tenths of an arcsecond in size, and are distributed over a region approximately 40″ long and 20″ wide. A simple statistical analysis indicates that the clustering is probably real. The size and appearance of the individual objects, their blue colors, and their clustering, leads us to speculate that they are associated, and that they considerably more distant than the cluster CL 0939+4713 at $z = 0.40$, probably at a redshift $z > 1$.

Among the strongest concentration of these objects is an unresolved, extremely blue object with the spectrum of a QSO at $z = 2.055$. We suggest that many of the small, faint objects could be physically associated with this QSO. If so, we may have observed a population of very distant, but in other respects "typical," galactic or protogalactic objects, by detecting sites of strong star formation in what appears to be an early and possibly chaotic stage of galaxy development. Objects of similar size and brightness are spread around the field; their number density represents a significant fraction of the faint galaxy counts done with ground-based imaging. This suggests that the ability to resolve small structure with HST may have focused our attention on an important class of objects that might be the best examples to date of nascent galaxies, the ancestors of common galaxies like the Milky Way.

Subject headings: galaxies: clusters: individual (CL 0939+4713) — galaxies: distances and redshifts — galaxies: evolution — galaxies: formation — quasars: general

1. INTRODUCTION

No target of extragalatic astronomical research has been more elusive than primeval galaxies—first generation stars in structures that were to evolve into the ubiquitous forms of today's cosmic landscape. Our ability to see unimpeded to remote epochs, as demonstrated by the detection of quasars out to redshifts $z \sim 5$, coupled with the expectation of an enormous radiation flux that must have accompanied the formation of the now-old stellar populations of our own Milky Way and neighboring galaxies, has long sustained our hopes of actually witnessing the birth of ancestral star systems (Partridge & Peebles 1967). As reviewed by Koo (1986), intensive searches with optical imaging have explored and found empty large areas in the parameter space of limiting magnitude and number density, areas which might have harbored nascent galaxies. While isolated examples of what are almost certainly primeval galaxies have been found, particularly in the investigation of faint radio sources (McCarthy et al. 1987; Eisenhardt & Dickinson 1992), these are by their nature rare and exceptional objects. The great majority of objects which evolved into the population of common present-epoch galaxies has not yet appeared.

One might have expected the *Hubble Space Telescope* to push the search frontier, but the potential contribution of *HST* was downplayed by Bahcall, Guhathakurta, & Schneider (1990), in their preview of what the deepest *HST* images would reveal. They reminded us that, for the geometries of standard cosmologies, galaxies retain relatively large diameters of an arcsecond or more even at very large redshifts ($z > 1$) and lookback times. One expects, then, that the advantage that *HST* holds over ground-based imaging, in its ability to detect faint stars and other "seeing-limited" sources, would not be realized for galaxies. Bahcall et al. concluded that *HST* was unlikely to record any class of galaxies not already detected from the ground. While this reasoning may have been correct, it may have underemphasized the potential importance of *HST* in culling, from the myriad of faint, fuzzy galaxy images recorded with Earth-bound telescopes, those objects in which a significant portion of the light might come from very small substructure, as originally suggested by Meier (1976). Distant and "primeval" galaxies might well contain sites of star formation and active nuclei (AGN) cores whose small sizes would lead to preferential detection with *HST* compared to ground-based observations.

Here we report a potential discovery of just this sort—the possible detection of a group of nascent galaxies at $z > 1$, perhaps as distant as $z = 2.055$. Our evidence, significant but still circumstantial, comes from a deep *HST*–Wide Field Camera image of the rich cluster of galaxies CL 0939+4713 at $z = 0.40$. The field contains a clustering of some 30 very faint, small objects. Set among them is a QSO at $z = 2.055$ found by Dressler & Gunn (1992) in their study of CL 0939+4713. If the cluster of faint objects is associated with the QSO, they cover several hundred kiloparsecs at $z = 2$ and are observed in the far-UV. We suggest that these objects, the brighter parts of which are subgalactic in size, are luminous star-forming regions of some few or tens of young galaxies whose full morphology is hidden below the detection limit of the *HST* image.

2. OBSERVATIONS

Our data come from a Wide Field Camera exposure of ~6 hr with filter F702W of a field containing the very rich cluster of galaxies CL 0939+4713 located at $z = 0.40$ (Dressler & Gunn 1992, hereafter DG). The principal aim of our program is to obtain morphological information for galaxies in several rich clusters, results that will be presented elsewhere. The 10 single-orbit exposures (split into two groups of five by a planned displacement of [2″, 3″] of *HST* pointing) had biases removed and were divided by flat fields in the STScl pipeline. We used the IRAF reduction package IMALIGN to register the two sets of frames and IMCOMBINE to coadd, with keyword "SIGCLIP" = 2.5 to remove cosmic rays. We have analyzed both raw and deconvolved images. The deconvolved images were made using the STSDAS reduction package LUCY, employing a single star image per field taken from a 20 s exposure of NGC 188. This is sufficient to clean the images of the halo of light associated with the PSF. We show only the deconvolved images here with the claim that all features under discussion are seen on both the original as well as deconolved frame.

The level of detail visible on these frames is impressive. In Figure 1 (Plate L4) we show one quadrant, chip 4 of the WFC. The several tens of bright galaxies are members of the cluster CL 0939+4713 ranging from $20 < r_{\rm Gunn} < 22$. It is fairly easy to assign Hubble types to well over 100 galaxies in these frames; for example, the structure of the large, late-type spiral that appears to have a second nucleus ($x \sim 600$, $y \sim 300$) is well resolved even though it is only 2″ by 3″ in size.

Repeated scrutiny of this image for morphological information on the brighter galaxies led us to notice a spray of fainter objects along the top (north) edge of this frame. They are barely resolved but, for the most part, clearly nonstellar. This concentration, particularly the collection of some 15 objects between $400 < x < 600$, at $y \sim 700$ (just left of top center), is far more conspicuous than any other grouping of faint objects in our seven other frames. There is an obvious resemblance here to the way a cluster of galaxies such as our target CL 0939+4713 at $z = 0.40$ appears on a wider field image such as a very deep photographic plate taken with the 48 inch (1.2 m) Palomar Schmidt telescope. On the other hand, this is *not* what we expect upon reaching redshifts $z \geq 1$—these objects appear many times smaller and closer together than the foreground galaxies at $z = 0.40$, but in any conventional cosmology galaxies do not continue to decrease substantially in size at redshifts $z > 1$ (see, e.g., Peebles 1971, Fig. VI-5).

Assuming for the moment that this is a genuine clustering of objects at a common distance, rather than a statistical accident, the obvious question is what is this clustering of faint images that are obviously not stars but are too small to be galaxies as we normally recognize them? A clue, we believe, comes from a serendipitous observation by Dressler & Gunn (1992). The most conspicuous member of this putative very distant cluster is an unresolved blue object, number 440 in the DG catalog, whose spectrum is that of a QSO or Seyfert 1 with redshift $z = 2.055$. In Figure 2 (Plate L5) we provide an enlargement of this region of the *HST* image on which the QSO is marked. This relatively bright object, $r = 21.35$, is flanked by two fainter, probably unresolved images (at 10 o'clock and 2 o'clock) that are only 0″.3 and 1″.1 away. There appears to be a bridge between the QSO and the object at 10 o'clock. This feature is hard to see on the raw image, so it may be a result of the Lucy deconvolution; subsequent *HST* observations should resolve this issue. The QSO has a $g - r$ color of -0.04 (though both the magnitude and color include some light from at least the closer of these two companions). The spectrum of object 440, displayed in Figure 3, clearly shows broad C III], C IV, and Mg II emission and a flat continuum.

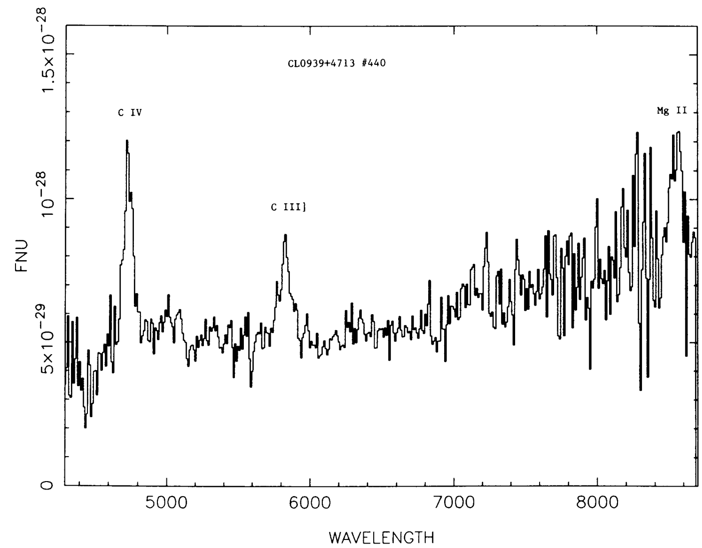

FIG. 3.—Spectrum of the QSO, obtained by Dressler & Gunn, from which the redshift of 2.055 was determined.

Although we can only claim guilt by association with the present data, it seems possible, if not probable, that the cluster of faint objects is at the same redshift as the QSO. A qualitative but important argument is based on the similarity in size ($d < 1''$) and brightness ($22 < r < 25$) that directed our attention to them—simply put, these objects *look* as if they are associated.

More quantitative arguments are provided by the statistics of the association. Using the IRAF routine QPHOT, we derived instrumental magnitudes for all objects on this frame and referenced them to the r magnitudes of 56 objects in the DG sample. On this new scale, the QSO magnitude (in this case just the central image) is $r = 21.90$. From counts as a function of magnitude, we conclude that our sample is relatively complete to $r = 24.75$. Within this magnitude interval, $21.90 < r < 24.75$, there are 86 objects within the frame. Figure 4 is a map of the distribution of this subsample; a circle of radius $R = 10''$ is drawn around the QSO in order to focus on the most conspicuous area of this suspected cluster (although we believe, based on appearances alone, that this association continues across the top right-hand side of the frame to include another 20 or more objects, as shown in Fig. 5). Within the 10″ radius circle there are 12 objects in addition to the QSO within this magnitude range. Since this area is 4.96% of the entire frame, we expect 4.26 objects on average within this circle. Applying Poisson statistics (i.e., assuming that the objects are

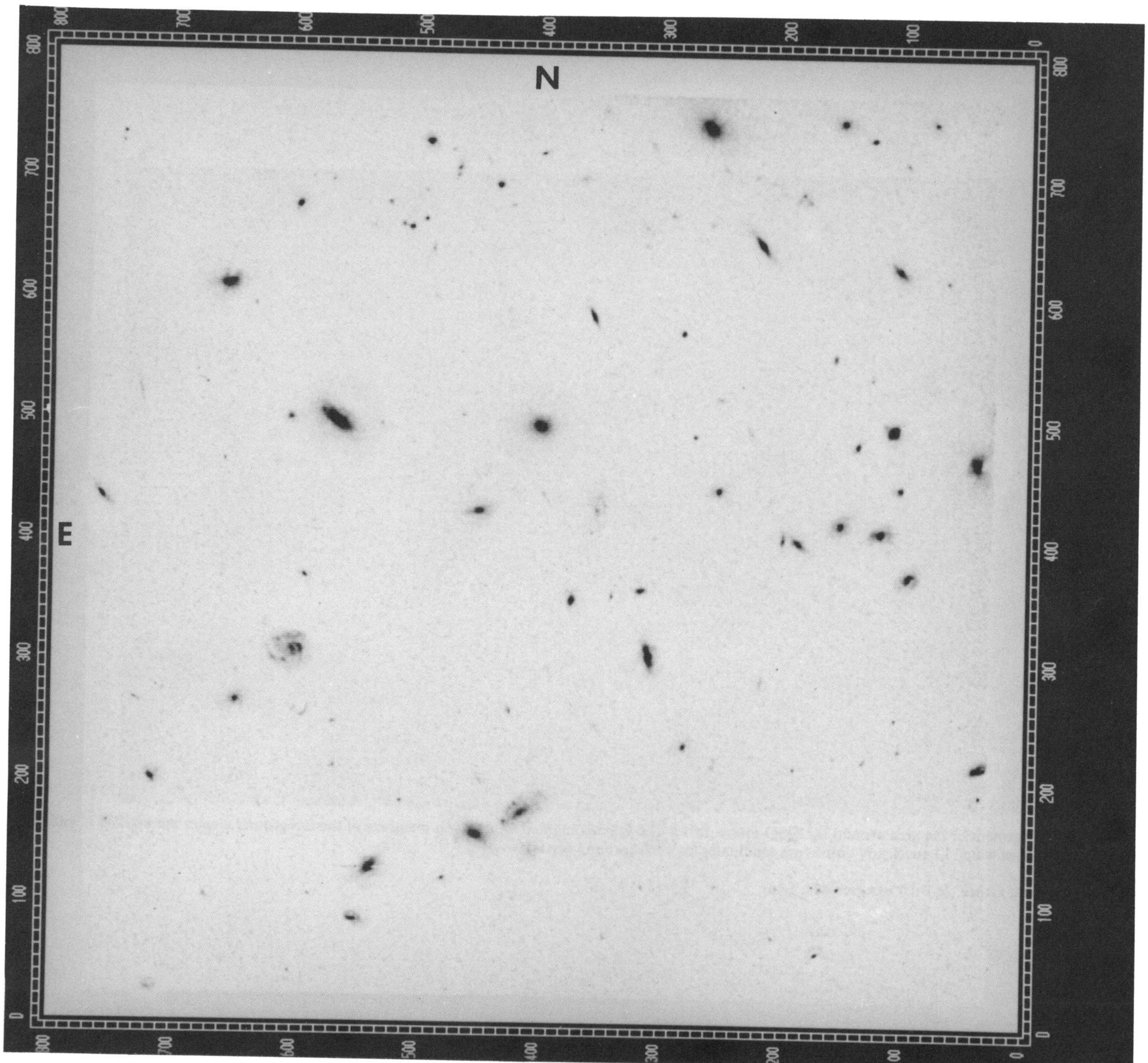

FIG. 1.—One WFC frame of a 6 hr exposure with F720W of a field containing the rich cluster CL 0939+4713 at $z = 0.40$. North is up, and east is to the left. Approximately 40 well-resolved galaxies with magnitudes $20 < r < 22$ in this cluster are visible. The clustering of fainter objects, $22 < r < 25$, discussed in this paper runs along the north edge ($y \sim 700$) between $600 < x < 150$.

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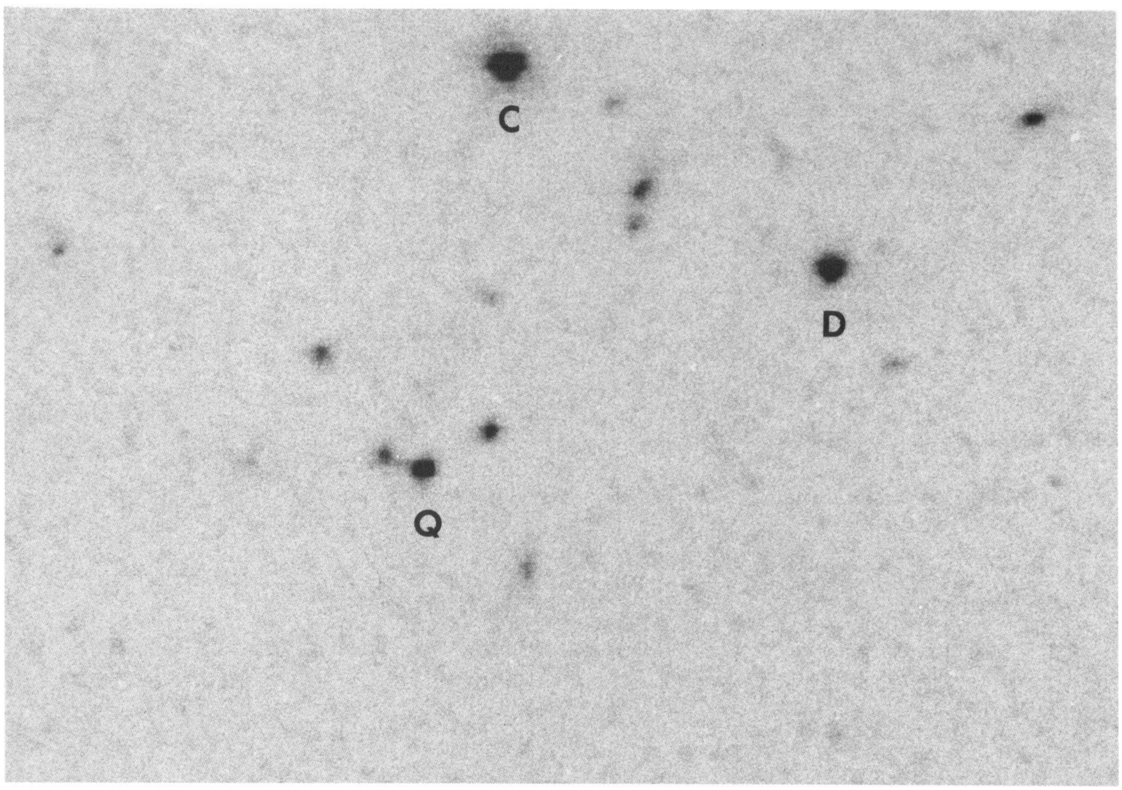

FIG. 2.—Enlargement of the area around the QSO at $z = 2.055$. The QSO is marked Q, and two members of the foreground cluster are marked C and D. The other faint objects, of which 13 are clearly visible, are candidates for a background cluster.

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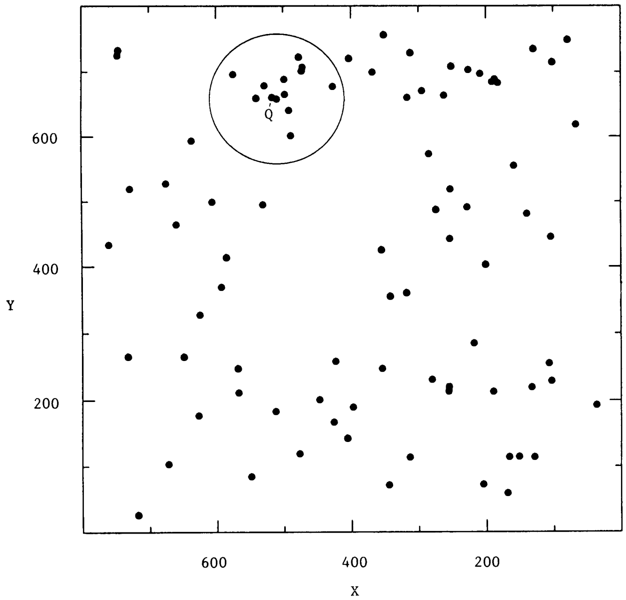

FIG. 4.—Map of the distribution of objects $21.90 < r < 24.75$. The QSO is marked at the center of a circle of 10″ radius, which was used in the statistical tests described in the text.

not physically associated and thus unclustered), the chance of finding 12 objects around the QSO is very small: $\boldsymbol{P} = 1.06 \times 10^{-3}$.

As an alternate approach, we may calculate the probability of finding a QSO associated by chance with a cluster of objects. We first calculate, following Politzer & Preskill (1986), the chance of finding 13 objects in *any* circle of 10″ radius within this (single-camera) field to be $\boldsymbol{P} = 0.058$. Adding to the statistical weight is the western extension of this clustering, which includes another circle of 10″ radius containing 12 objects. We do, therefore, have reason to believe that this is a real clustering of objects that suggests a physical association. The surface density of QSOs with $r < 23$ is only about 200 per square degree (Kron et al. 1991), i.e., only one field in 10 the size of a WFC frame should contain a QSO. The probability of finding a QSO within a circular area of $r = 10''$ is only 5×10^{-3}. Combining this with the probability of clustering derived above, we find that the joint probability of a chance association within this frame between a cluster of this richness and a QSO is only 3×10^{-4}. These are a posteriori statistical arguments, to be sure, but they are suggestive.

Of this collection of faint objects, only the QSO has a measured redshift. However, we do have a some color information for many of the brighter objects in the group from ground-based CCD imaging with the 200 inch (5 m) Hale telescope. In Figure 5 (Plate L6) we show the more complete region from the QSO westward and compare the *HST* image and these g, r, and i images. Though the seeing on these frames is mediocre (1″.4 FWHM), they are moderately deep because they are fairly long exposures (a total of ~ 5000 s in g and ~ 2500 s in r, and i). We have marked in Figure 5 the QSO, a very blue object, and probable members of the foreground cluster (indicated by the letters A–H) for color comparison with the candidates for the distant cluster, which are labeled in Figure 5 as 1–8. In particular, objects 2 and 8 are extremely blue, comparable in color to the QSO. However, even the other six are also noticeably bluer than the members of the foreground cluster. Furthermore, the colors provide evidence that the more distant objects are at a redshift $z > 1$. With the exception of object 3, none of the numbered objects are noticeably brighter in r compared to g, or i compared to r, which indicates that the 4000 Å break lies redward of 8000 Å.

The bluest object, number 2, is particularly intriguing. The object (actually resolved into a pair of objects in the *HST* frame) is most prominent in the g-band image, which corresponds to a rest frame wavelength centered at $\lambda \sim 1600$ Å. Such a blue color—a spectral energy distribution that is nearly flat, like the QSO—indicates a stellar population dominated by O and B stars. If object 2 is a distant object, it may well qualify as a "primeval" galaxy, since we could be seeing its first significant epoch of star formation. Considering the k-correction at $z > 1$, the other objects must be very blue in comparison with present-epoch galaxies. However, their populations might include stars up to $\sim 10^9$ yr in age, so the terms *young* or *nascent* galaxies might be more appropriate than *primeval.*

Figure 5 highlights the substantial gain in detecting faint objects of small size with *HST*, though it is clear that long CCD exposures in subarcsecond seeing with large ground-based telescopes will be able to improve substantially on the data presented here.

We have speculated that the entire collection of objects are at the distance of the QSO, though, again, our evidence is circumstantial. Perhaps the strongest statements we can make are that these objects are almost certainly not at redshifts $z < 0.7$, judging by their complete dissimilarity to the galaxies at $z = 0.40$ spread over the frame, and that their colors suggest $z > 1$. However, another interesting possibility is that the objects in question are in a cluster at a redshift in the interval $1.0 < z < 1.5$ and that the QSO is either unassociated or lensed by a galaxy in this "foreground" cluster. Since the concentration of galaxies is not very strong, and the QSO is not well centered, it seems unlikely that the amplification of its light would be significant enough to be responsible for this "coincidence." Without additional measurements we cannot rule out the possibility that the cluster is at a somewhat lower redshift, but this would only weaken, rather than invalidate, the discussion below as to the nature of these faint extended objects.

Association of faint objects with quasars is well documented, with findings that seem to be consistent with what has been detected here. For example, in continuum "broad-band" imaging around quasars, Lehnert et al. (1992) and Heckman et al. (1991) have found several to more than 10 faint companions in fields of ~ 0.1 arcmin^2, an area similar to that containing the 12 companions closest to the quasar in this field. Also, narrow-band searches in Lyα (e.g., Djorgovski et al. 1985; Hu et al. 1991) have been particularly effective in discovering close companions that are the redshift of the QSO, though in many of these instances there is ambiguity about whether these are young galactic companions or simply gas clouds whose emission is powered by the intense radiation of the quasar.

3. DISCUSSION

We have suggested that many of the faint objects of small size in this frame are considerably more distant than the galaxies in CL 0939+4713 at $z = 0.40$. The principal evidences for this are their colors which are bluer than the galaxies in CL 0939+4713, despite the expectation of a larger k-correction, and their small sizes—the galaxies in the foreground cluster

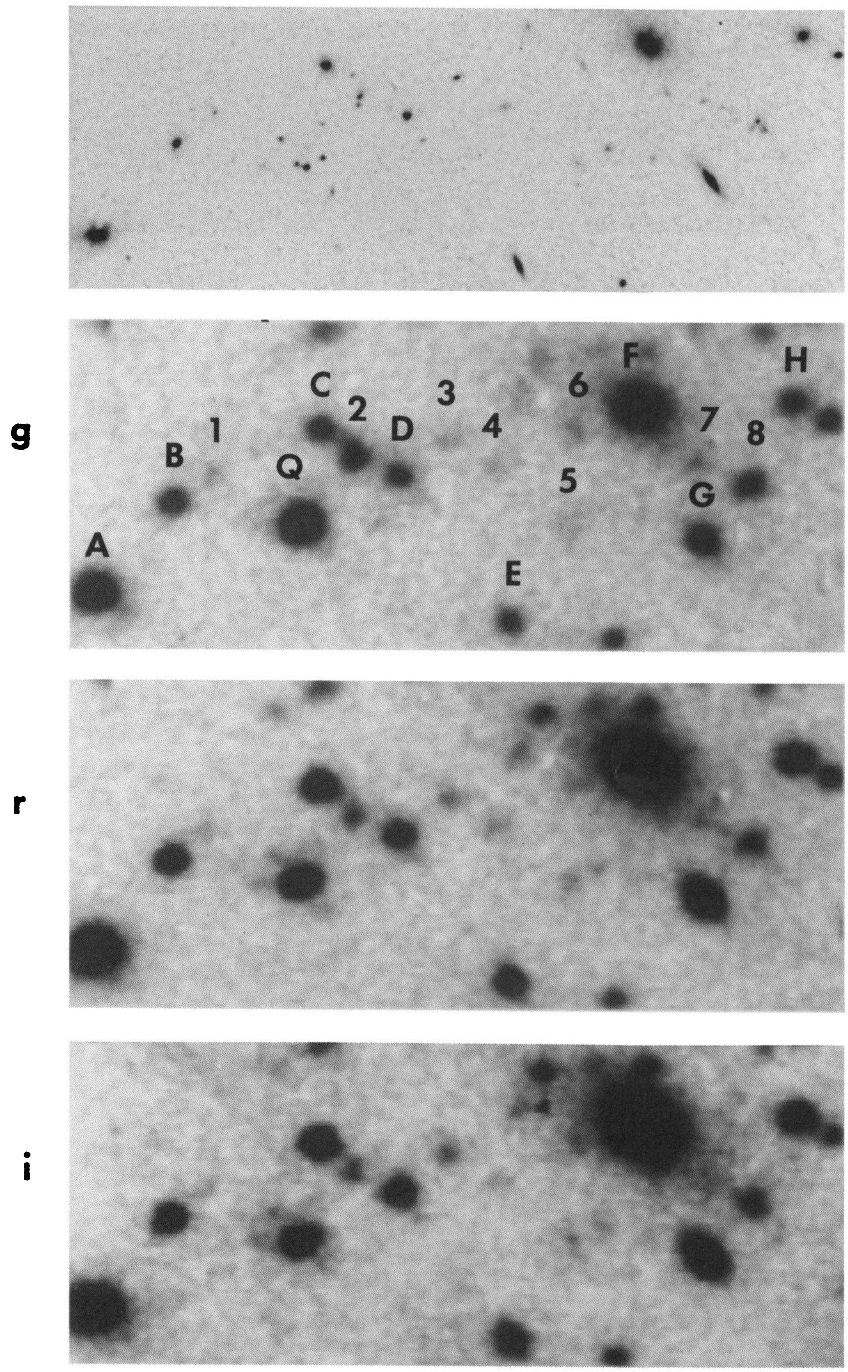

FIG. 5.—The area of the putative distant cluster, as observed with *HST*-WFC with the F702W filter, as compared to moderately deep CCD imaging done with the 4-Shooter on the Palomar Hale Telescope, in the colors Gunn *g*, *r*, and *i*. Probable members of the foreground cluster are labeled with the letters A–H. The QSO is marked by the letter Q, and the possible members of the background cluster are numbered 1–8. Objects 2 and 8 are extremely blue, comparable in color to the QSO, but all the numbered galaxies are much bluer than the members of the foreground cluster CL 0939+4713.

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also show small structures but their full extent of an arcsecond or more are easily visible. From the ratio of small- to large-aperture magnitudes, we find that all but one of the objects within 10″ of the QSO are nonstellar. It is conceivable that the smaller objects are fragments of low-luminosity, late-type galaxies that are also at intermediate redshift ($z < 1$) like the cluster CL 0939+4713. Since CL 0939+4713 contains many late-type galaxies, but no distribution of objects such as these, this possibility seems unlikely.

Referring to Peebles (1971), 1″ ranges from 7–8 kpc ($H_0 = 100$, $q_0 = 0.0$) to 8–11 kpc ($H_0 = 50$, $q_0 = 0.5$) for redshifts $z \geq 1$. Thus, the luminous parts of these clustered objects have physical diameters of only a few kiloparsecs! Obviously, then, each one of the ~30 objects we have identified is not an individual galaxy, since there are several cases where two or more objects are contained within a circle with a diameter less than 10 kpc. Indeed, the entire region under discussion, some tens of arcseconds, is only 200–400 kpc in extent—a structure which might be thought of as the antecedent of a small group or cluster core.[1] What, then, are these objects? We hypothesize that many are regions of intense star formation in young, coalescing systems. These regions of high surface brightness, $20 < \mu_r < 22$ mag arcsec^{-2} might overlie larger, more diffuse populations with surface brightnesses $\mu_r > 23$, to which these observations are relatively insensitive. We are tempted to claim that these HST images reveal a much different morphology for galaxies than is seen today or even at $z = 0.4$. But it is important to remember that these images are taken in the far-ultraviolet if the redshift is $z = 2.055$, and certainly even present-day spirals appear much lumpier when imaged in this band. It is too soon to conclude anything about overall morphology and, indeed, the WF/PC-2 will probably be required to reach the necessary depth. But there is certainly the suggestion that the *Hubble* atlas at $z = 2$ may be another book altogether.

If these are regions of intense star formation, subsequent observations may, despite the faintness of these objects, be able to confirm their association with the QSO through the detection of Lyα, C III], C IV, or Mg II. Slit spectroscopy of even the brightest of these candidates will be challenging to say the least—the new generation of large optical telescopes like the Keck 10 m may be necessary. On the other hand, narrow-band imaging in these emission lines could be an effective way to verify an association with the QSO. This is probably within reach of 4 m class telescopes in very good seeing conditions. Deeper broad-band imaging in the optical, to assess the colors of the fainter objects, and near-infrared *K*-band imaging to look for light coming from an older population, could also be pursued from the ground under excellent conditions. Our team has scheduled a *HST* two-orbit observation in F555W which should detect any fainter members that are extremely blue.

Finally, we note that, although we have been led to identify these as very distant objects by their association with the QSO and by comparing them to the lower redshift cluster galaxies of CL 0939+4713, they may be representative of a ubiquitous population of young or primeval galaxies. The number counts of faint galaxies in noncluster fields, in random directions in the sky, is ~50 arcmin^{-2} to $r = 24.75$ (Tyson 1988). This is comparable to the number density on this *HST*-WFC frame of 86 objects over an area of 1.8 arcmin^2 in the magnitude interval $21.90 < r < 24.75$. If we exclude the 12 objects that are within 10″ of the QSO, the QSO itself, and the 13 objects directly west, we are left with 50 objects spread over the frame in this magnitude range. Visual inspection indicates that approximately 20 of these are large systems, probably members of CL 0939+4713 or at a comparable distance. However, the remaining 30 are indistinguishable from the objects clustered around the QSO. Adding this to the original 25, we are left with a density of 30 objects arcmin^{-2}. This means that a population approaching 50 arcmin^{-2} (10^5 objects deg^{-2}) could share the characteristics of those surrounding the QSO at $z = 2.055$. These could indeed be the ancestors of a significant fraction of the large galaxies we see today.

[1] We think it unlikely that these are all objects in a *single* galaxy halo, since that would imply that little dissipation has occurred, while the presence of so many high-density lumps suggests otherwise.

4. CONCLUSIONS

We have identified a clustering of 15–30 objects that appear to lie at a common distance, $z \geq 1$, and suggest, specifically, that they could be associated with an adjoining quasar at $z = 2.055$. Should this association be confirmed, it means that we can begin to study a group of objects that may represent the early stages of formation of what will become fairly typical galaxies. The fact that these young or nascent galaxies have been detected in this way would further indicate that galaxies, to the extent they had "formed" by $z = 2$, were still very inhomogeneous, with very prominent sites of star formation rising, perhaps chaotically, above whatever larger scale organization had been accomplished. It seems clear, at least, that these "galaxies" would bear little resemblance to today's galaxies; thus, in a very real sense, evolution of a fundamental nature would have been observed.

These conclusions, thus, could have far-reaching implications for the way in which galaxies were born. Though the presence of a QSO may have focused our attention on these objects, it appears that others like them are scattered over the field and that they represent a significant fraction of the faint galaxy counts made with ground-based imaging. Whatever these objects are, they will be challenging to study due to their small size and faintness. But *HST* may well have pointed the way toward a class of objects that will be invaluable in the study of galaxy formation—the best examples to date of what might fairly be called nascent galaxies.

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