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THE SERENDIPITOUS DISCOVERY OF A GROUP OR CLUSTER OF YOUNG GALAXIES AT $z \simeq 2.40$ IN DEEP *HUBBLE SPACE TELESCOPE*[1] WFPC2 IMAGES

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ABSTRACT

We report the serendipitous discovery of a group or cluster of young galaxies at $z \simeq 2.40$ in a 24 orbit *Hubble Space Telescope*/WFPC2 exposure of the field around the weak radio galaxy 53W002. Potential cluster members were identified on ground-based narrowband redshifted Lyα images and confirmed via spectroscopy.

In addition to the known weak radio galaxy 53W002 at $z = 2.390$, two other objects were found to have excess narrowband Lyα emission at $z \simeq 2.40$. Both have been spectroscopically confirmed, and one clearly contains a weak active galactic nucleus (AGN). They are located within 1′ of 53W002 or $\sim 0.23\ h_{100}^{-1}$ Mpc ($q_0 = 0.5$) at $z \simeq 2.40$, which is the physical scale of a group or small cluster of galaxies. Profile fitting of the WFPC2 images shows that the objects are very compact, with scale lengths $\simeq 0\farcs1$ ($\simeq 0.39\ h_{100}^{-1}$ kpc), and are rather faint (luminosities $< L^*$), implying that they may be subgalactic-sized objects. We discuss these results in the context of galaxy and cluster evolution and the role that weak AGNs may play in the formation of young galaxies.

Subject headings: galaxies: clusters: general — galaxies: distances and redshifts — galaxies: evolution — galaxies: formation — quasars: general

1. INTRODUCTION

To gain a better understanding of galaxy formation we must observe a representative sample of galaxies over a wide range of look-back time. The difficulty, however, lies in the detection of a complete sample of galaxies with spectroscopic redshifts in excess of 1.0. Searches based on absorption lines seen in the spectra of background quasars, e.g., Mg II or damped Lyα (Elston et al. 1991; Pei, Fall, & Bechtold 1991; Turnshek et al. 1991; Lowenthal et al. 1991, 1995, hereafter L95; Wolfe et al. 1992; Macchetto et al. 1993, hereafter M93; Francis et al. 1996; Steidel, Dickinson, & Persson 1995), as well as serendipitous discoveries (Djorgovsky et al. 1985; Steidel, Sargent, & Dickinson 1991), have so far yielded relatively few high-z galaxies. Since most powerful *nearby* radio galaxies are luminous ellipticals, which often occur in groups or clusters, it may be possible to assemble a sample of galaxies through their association with known high-z radio galaxies or QSOs (McCarthy et al. 1987; Lilly 1988; Hu et al. 1991; Windhorst et al. 1991, hereafter W91; Dressler et al. 1993). The opportunity to examine *several* galaxies at the same redshift in such a high-z group would be extremely valuable to the study of galaxy evolution.

In this Letter we report the serendipitous discovery and consequent follow-up of a group or cluster around 53W002, a known weak steep-spectrum compact radio source at $z = 2.390$ (W91). In § 2 we present the observations, including both narrowband imaging and spectroscopy, which confirm our initial discovery. We give our results in § 3 and discuss their implications in § 4.

2. OBSERVATIONS

2.1. *The HST/WFPC2 Images*

In 1994 May–June, we obtained a 24 orbit exposure of 53W002 and its surroundings with the refurbished *Hubble Space Telescope*/WFPC2. The $0\farcs07$ resolution images of 53W002 confirmed that $\sim 20\% \pm 4\%$ of its central flux comes from an unresolved point source (Windhorst & Keel 1995, hereafter WK95). Its active galactic nucleus (AGN) is surrounded by a clearly extended and fairly symmetric $r^{1/4}$-like light profile with $r_e \simeq 1\farcs1 \pm 0\farcs1$ ($\simeq 4.3\ h_{100}^{-1}$ kpc), consistent with that of nearby *luminous* early-type galaxies. (For details, see W91; Windhorst, Mathis, & Keel 1992, hereafter WMK92; Windhorst et al. 1994; WK95.)

Figure 1 (Plate L3) shows a color image constructed from the 5.7 hr $V_{\rm F606W}$ and $I_{\rm F814W}$ WFPC2 images for the central portion of this field. Potential cluster members, chosen on the basis of their similarities in appearance to the serendipitously discovered object A, are labeled B through J. Object 4 is from W91 and WMK92 and is discussed later. Details of the WFPC2 observations are given by WK95 and Driver et al. (1995). The dark *HST* sky at the north ecliptic pole allowed galaxies to be imaged down to $V \simeq 27$ and $I \simeq 26$ mag, while the few stars in the images can be detected down to $V \simeq 28.5$ mag (see WK95).

[1] Based on observations with the NASA/ESA *Hubble Space Telescope* obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA Contract NAS 5-26555.

[2] Optical observations obtained in part at the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

[3] Optical observations obtained in part at the Steward Observatory 90 inch Telescope, a facility of the University of Arizona.

[4] Observations made at Palomar Observatory are part of a collaborative agreement between the California Institute of Technology and the Carnegie Institution of Washington.

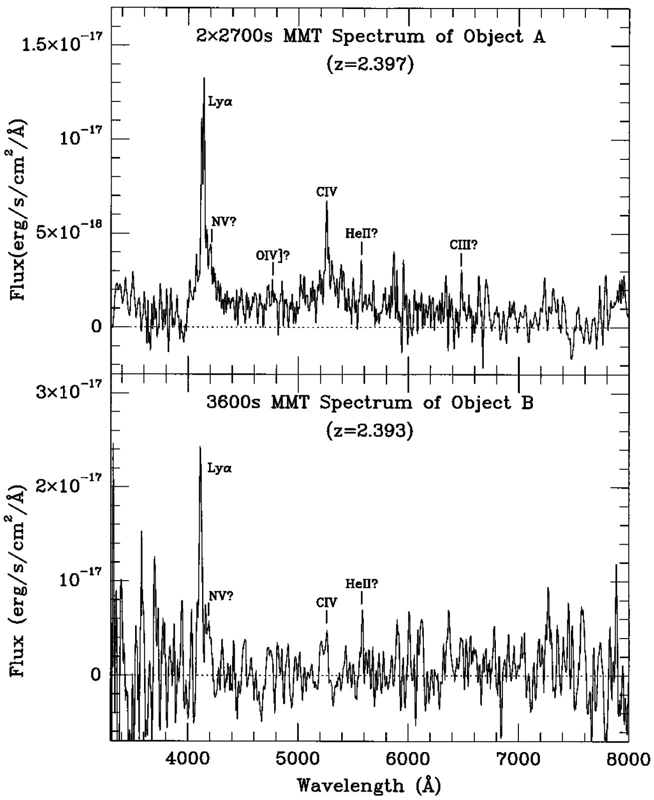

FIG. 2.—*Top*: 2 × 2700 s long-slit spectrum of object A showing the emission lines of Lyα, N v, C IV, and possibly O IV, He II, and C III at $z = 2.397$. The shape of the continuum and the relatively narrow lines with broad wings are indicative of a weak AGN. *Bottom*: 1800 s long-slit spectrum of object B showing Lyα and C IV, with possibly N v and He II at $z = 2.393$.

2.2. *MMT Spectra*

As part of routine spectroscopic follow-up on the brighter galaxies in the field, we serendipitously discovered a blue compact object (labeled A in Fig. 1) with $V_{F606W} = 23.07$ mag at the same redshift as 53W002 to within ~400 km s^{-1}. Its spectrum shows Lyα, N v, C IV, and possibly O IV, He II, and C III emission lines at $z = 2.397$, some of which have broad wings indicative of a weak AGN component (see Fig. 2 [*top*]). The spectrum was obtained with the Blue Spectrograph at the MMT using a 300 grooves mm^{-1} grating giving ~9 Å resolution and has been smoothed to ~18 Å resolution to increase the signal-to-noise ratio. In 1995 April, Lyα and possibly C IV at $z = 2.393$ were found in a short 1800 s exposure of object B (Fig. 2 [bottom]), a cluster candidate discovered in our narrowband Steward images. The spectrum was obtained with the MMT Red Spectrograph and low-resolution (~20 Å) 150 gpm grating.

2.3. *Steward 90 Inch Telescope B-Band and Narrowband Redshifted Lyα Images*

In order to search for other potential cluster members, a narrowband filter centered at 4130 Å (Lyα at $z \simeq 2.40$) was quickly constructed by D. Marcus for use at the Steward Observatory 90 inch (2.3 m) telescope. The blue-sensitized Loral 800 × 1200 CCD was used to image a 3′ × 4′.5 field at 0″.225 $pixel^{-1}$ in both the "Lyα" and Johnson *B* filters. Because of poor weather, we were able to obtain only two 3600 s exposures in Lyα and one 720 s exposure in *B*. These two images are displayed in Figure 3 (Plate L4) and are equally deep despite their different exposure times, given the relative widths and throughputs of the two filters (~150 Å FWHM and ~60% transmission for Lyα vs. ~1100 Å FWHM and ≳90% transmission for *B*). A deeper (6600 s) Steward 90 inch *B*-band exposure of a 3′ × 3′ area of the same field was taken in 1990 by W91. The three spectroscopically confirmed $z \simeq 2.40$ objects show obvious excess flux at 4130 Å and are indicated in Figure 3.

In addition to the *HST* and Steward images, we also have accurate Gunn *gri* photometry for all candidates from deep Palomar 200 inch (5 m) telescope 4-Shooter images (including objects 3 and 4 from W91, which were not detected significantly in the recent 90 inch telescope Lyα images). We predicted *B* magnitudes from the *gri* fluxes following W91 and used them to calibrate the 1990 and 1994 Steward 90 inch *B*-band images. We then calculated weighted averages of the 1990 and 1994 *B* magnitudes, which are more accurate than those of the shallow 1994 exposure alone. All photometry for the cluster members is given in Table 1.

3. RESULTS

We have updated the (4130 Å − *B*) versus (*B* − *g*) color-color diagram of W91 with photometry for *all* objects surrounding 53W002 (Fig. 4). Because the 4130 Å band is completely contained within the FWHM of the Johnson *B*-band, this diagram can locate objects with significant emission or absorption at 4130 Å. A featureless power law

TABLE 1

PHOTOMETRY OF CLUSTER MEMBERS

Name	R.A., Decl.	*U* (mag)	4130 Å (mag)	*B* (mag)	*V* (mag)	*I* (mag)	Gunn *g* (mag)	Gunn *r* (mag)	Gunn *i* (mag)	r_{hl}	Unresolved Point Source	M_v (mag)
53W002................	$17^h14^m14^s.74$,	23.24	22.41	23.37	23.01	22.48	22.87	22.83	22.78	1″.1	~20%[b]	−23.9
	50°15′28″.94	(0.36)[a]	(0.19)	(0.17)	(0.08)	(0.14)	(0.07)	(0.07)	(0.10)			
Object A...............	$17^h14^m11^s.27$,	22.57	21.97	23.15	23.07	22.30	21.69	22.29	22.77	≲0.1	~90	−21.4[c]
	50°16′08″.74	(0.42)	(0.17)	(0.36)	(0.14)	(0.12)	(0.06)	(0.07)	(0.16)			
Object B...............	$17^h14^m11^s.89$,	22.51	21.36	23.28	23.17	22.78	22.79	23.01	23.00	0.1	~52	−23.0[c]
	50°16′00″.51	(0.39)	(0.17)	(0.22)	(0.14)	(0.18)	(0.10)	(0.13)	(0.23)			

[a] Errors are the quadratic sum of the formal photometric errors (from photon statistics and the rms uncertainty in the surrounding sky fits) and the zero-point error. The latter is approximately 0.2 mag in *U*, 0.15 mag in Lyα, 0.12 mag in *B*, 0.07 mag in V_{F606W} and I_{F814W}, and 0.05 mag in Gunn *gri*.
[b] From WK95.
[c] Determined by using the distance modulus and *K*-correction of 53W002 (see, Table 5 in W91, based on the spectral evolution models of Bruzual 1983 for a young stellar population at $z \simeq 2.40$).

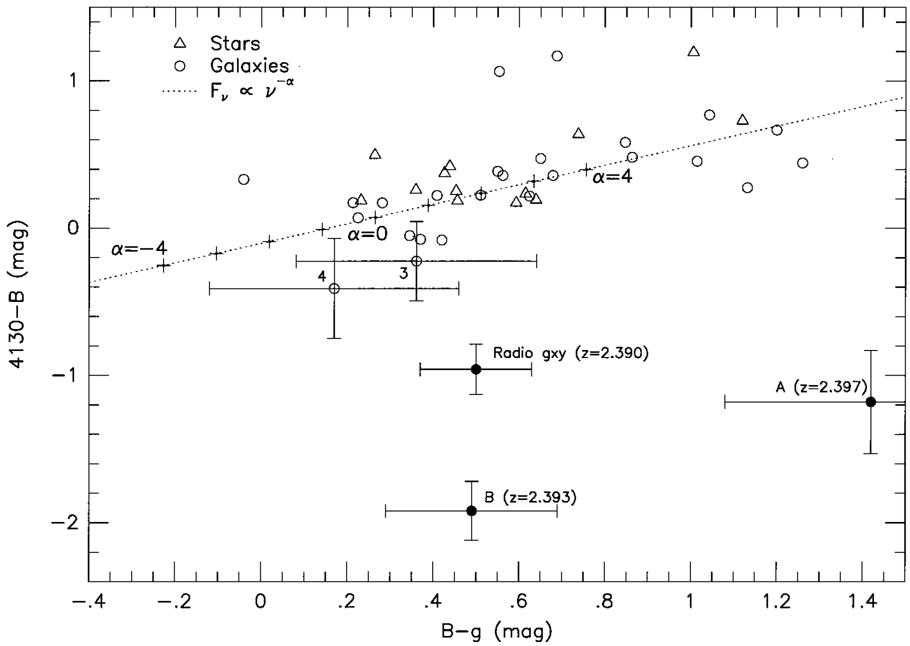

FIG. 4.—(4130 Å − B) vs. ($B - g$) color-color diagram for all objects surrounding 53W002, based on both recent 90 inch telescope data and older 90 inch telescope and Palomar data (W91). The locus of featureless power-law spectra ($F_\nu \propto \nu^{-\alpha}$) is indicated by the dotted line with the crosses marking integer values of α. Objects A and B are spectroscopically confirmed cluster members. The unusual location of object A in the diagram is most likely due to its variability.

($F_\nu \propto \nu^{-\alpha}$) is indicated by the dotted line with tick marks indicating integer values of α. The three spectroscopically confirmed $z \simeq 2.40$ objects lie significantly below the line, and objects 3 and 4 are borderline candidates (based on previous photometry; W91). Multiepoch photometry suggests that object A is variable on the timescale of years, which explains its unreasonable spectral index, placing it in the lower right-hand portion of Figure 4. It decreased in brightness by almost 1 mag in the Steward 90 inch telescope B-band images from 1990 to 1994, which is well beyond our largest possible photometric errors. Such variability is consistent with its Seyfert-like spectrum (Fig. 2).

Light profiles were generated, as for 53W002 in WMK92 and WK95, for objects A and B, and are given in Figure 5. Object A and the bright knot of object B are so compact that it was necessary to subpixellate their WFPC2 images 5 times (using biquintic interpolation). Effective radii were measured by assuming $r^{1/4}$ profiles, although exponential disks give similar results since their scale lengths are only ~1–2 pixels. Model profiles were then generated for a range of effective radii (following Keel & Windhorst 1993), convolved with a similarly subpixellated star, resampled to real WFC pixels and then subpixellated again to simulate the process used on the real data. Object A appears exactly stellar at small radii but is somewhat larger than the star point-spread function (PSF) beyond that. Its profile dips below the PSF at $r \gtrsim 7$ pixels ($0\farcs7$) because of its location in the "pyramid-shadow" region on the WFPC2 CCDs, while the reference star was much farther from the chip edge. Its "best-fit" effective radius is $r_e \lesssim 0\farcs1 \pm 0\farcs02$. Object B appears to be in an interacting (or otherwise disrupted) system or possibly has some reflected AGN light on one side from the compact component. Model fitting of the compact knot gives $r_e \simeq 0\farcs1 \pm 0\farcs02$. Note that the profile appears extended because it runs into its neighboring companion or cloud at $r \gtrsim 4$ pixels (see Fig. 1).

4. DISCUSSION

These findings raise several questions, the most interesting of which is why the confirmed cluster members (other than the radio source), after subtracting their likely point-source contributions, are so small and faint. Table 1 contains the half-light radii, point-source contributions, and absolute V magnitudes after point-source subtraction for the three $z \simeq 2.40$ cluster members. W91 found that at $M_v \simeq -23.6$

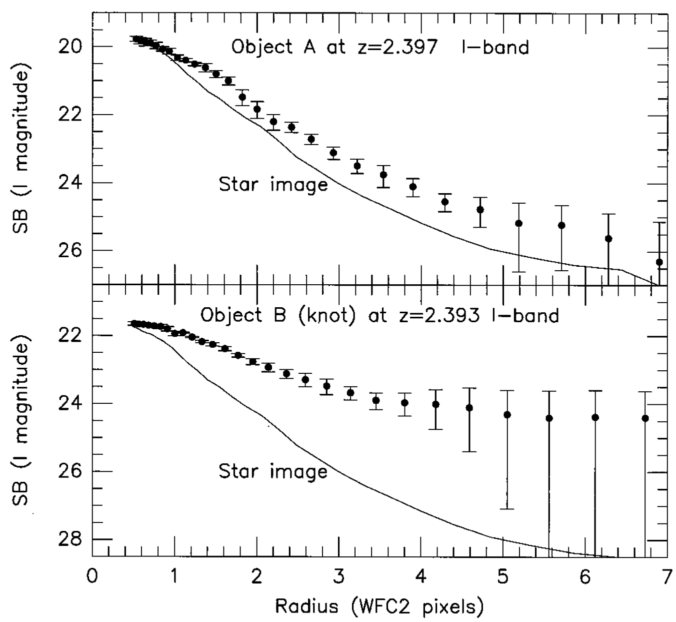

FIG. 5.—Light profiles for confirmed cluster members A and B. Both are very compact and were analyzed by subpixellating their HST images 5 times (using biquintic interpolation).

(assuming a 35% point-source contribution), 53W002 is only as luminous as an (evolving) L^* galaxy, whereas the more powerful radio galaxies at similar redshifts have luminous masses $\simeq$5–8 times greater (depending on the choice of cosmological parameters). The underlying stellar population in object A, which is about 2 mag fainter than 53W002, is thus most likely sub-L^*. This implies that perhaps we are seeing a young galaxy in the early stages of its development, the luminosity of which has not yet reached that of a typical L^* galaxy at $z \simeq 2.40$. Object B, which is as compact as object A, but does not necessarily contain an AGN based on the current spectral data, is also $\lesssim L^*$ at $z \simeq 2.40$. Estimating the absolute I magnitudes of these galaxies from Figure 6 of Casertano et al. (1995) also gives values below that of L^* galaxies ($M_I \simeq -22.7$).

Several selection biases must be noted, the most important of which is the preferential detection of cluster members with significant Lyα emission. This implies that the cluster members were found only because they contain weak AGNs. However, it has recently become clear that, despite issues of resonant scattering and destruction of Lyα photons by dust (Meier & Terlevich 1981; Hartmann et al. 1988; Terlevich et al. 1993), actively star-forming galaxies can in fact also have substantial Lyα emission (Calzetti & Kinney 1992; Valls-Gabaud 1993; L95). Several groups have now reported detections of Lyα emission from high-redshift galaxies, in which either the spatial extent or continuum shape suggest that it is produced by stellar photoionization rather than an active nucleus (Cowie & Lilly 1989; M93; Moller & Warren 1993; Giavalisco, Steidel, & Szalay 1994). Therefore, detectable Lyα emission does not always require an AGN.

Surface brightness selection effects caused by the small pixels in WFPC2, the cosmological $(1+z)^{3+\alpha}$ dimming, and the fact that we are observing at emitted wavelengths of 1800–2400 Å mean that the compact appearance of the cluster candidates must be viewed with some caution. The galaxies surrounding compact regions of strong UV light could be significantly larger than our measured sizes if their surface brightnesses are low enough to be completely lost in the WFPC2 sky + read noise, although we do attempt to avoid this problem by measuring half-light rather than isophotal radii.

Despite all these selection effects, it is tempting to speculate, in light of the present data, on the possibility that all galaxies start out with (weak) active nucleii. Will the compact, sub-L^* objects of this cluster in fact someday become the L^* galaxies we see at the present epoch? With respect to large-scale structure formation, can such a young cluster be explained by cold dark matter? We plan to address these questions in future work (Pascarelle et al. 1996). Current plans to extend these observations include 39 orbits in Cycle 5 with *HST*/WFPC2 using filters F410M (redshifted Lyα) and F450W (Johnson B) from which we will be able to locate compact Lyα-emitting components at scales 5–10 times smaller than those in this Letter.

In conclusion, we have shown substantial evidence for the existence of a group or cluster of young galaxies at $z \simeq 2.40$. The two confirmed members (other than the radio galaxy) appear to be compact and sub-L^*, with smooth well-formed inner light profiles. At least two, and possibly all three, show evidence for a weak AGN, suggesting that the presence of an AGN *may* be an integral part of galaxy formation, at least for galaxies of a certain luminosity. We look forward to being able to address many of the concerns about selection biases discussed here and to shed some light on the existence of such compact and faint objects with the superior quality of the *HST* images.

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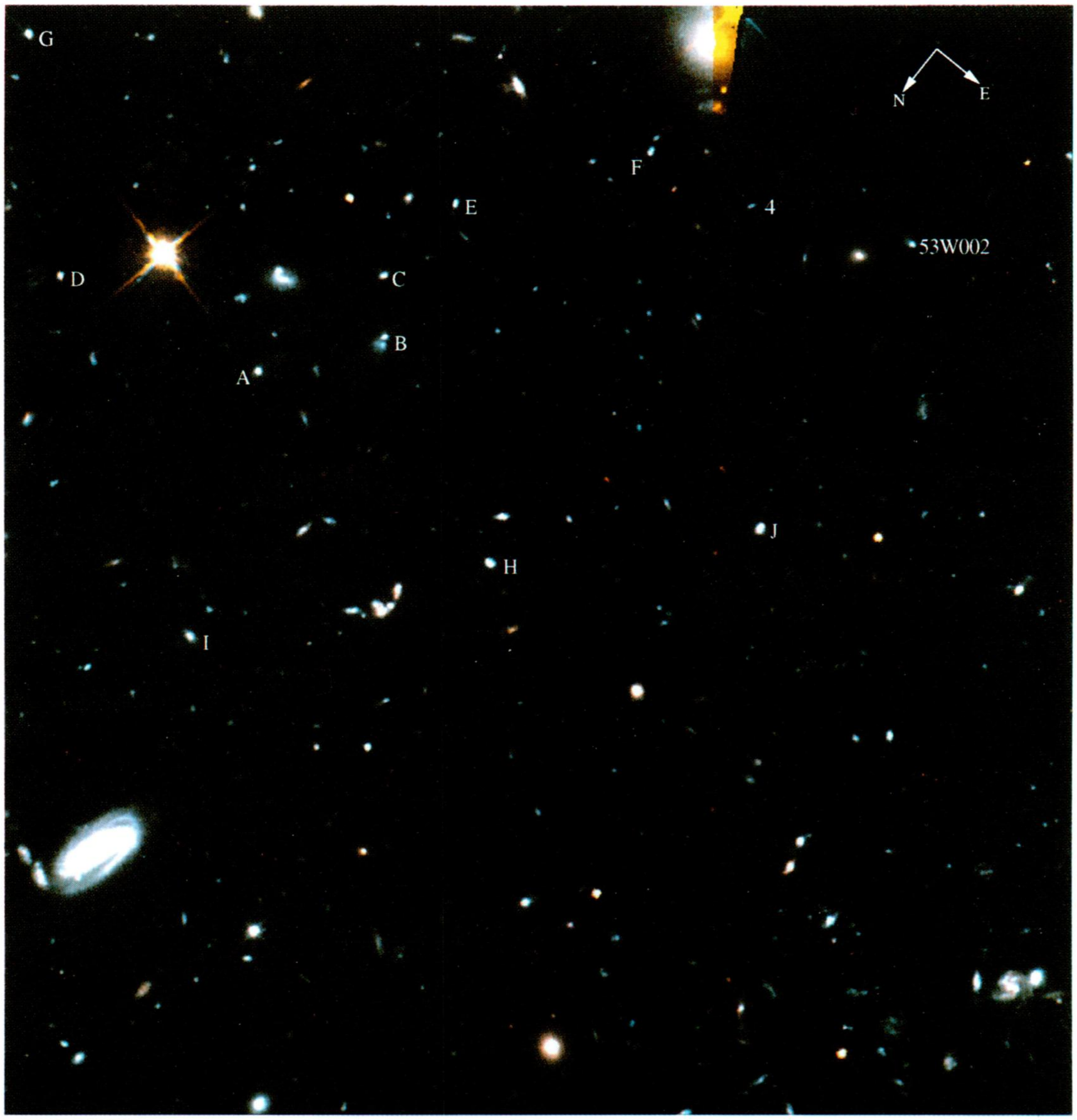

FIG. 1.—*HST* Cycle 4 color image of the field surrounding the weak radio galaxy 53W002 at $z = 2.390$. The image was constructed from a 5.7 hr V_{F606W} and a 5.7 hr I_{F814W} WFPC2 exposure and is about 72″ × 72″ with 0″.0996 pixels. Objects A and B are the spectroscopically confirmed cluster members at $z \simeq 2.40$.

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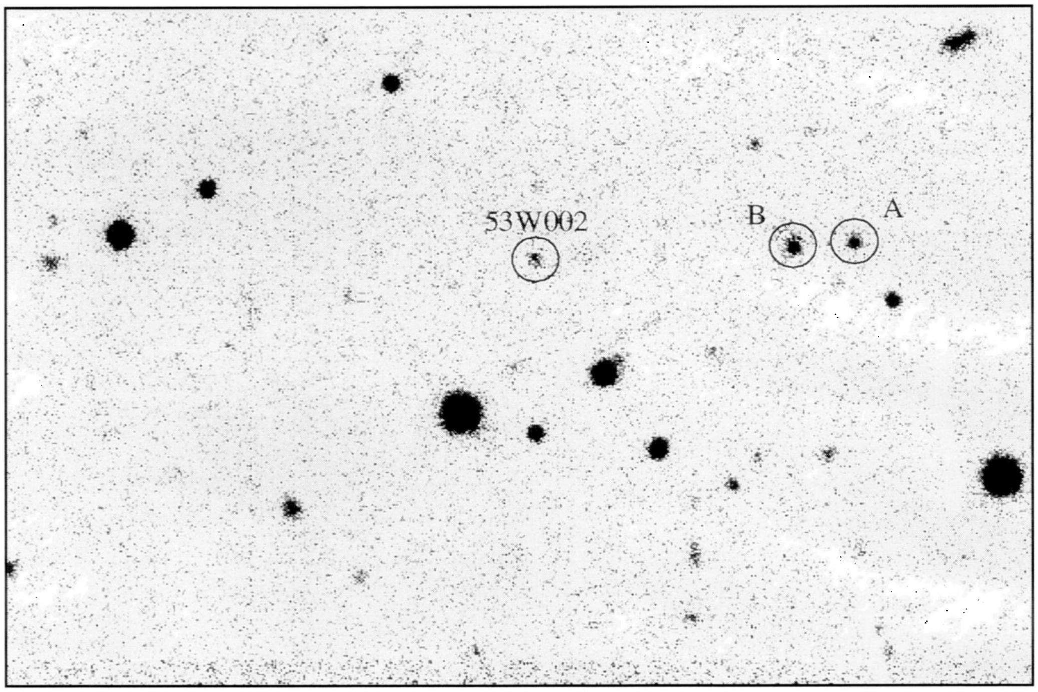

Fig. 3a

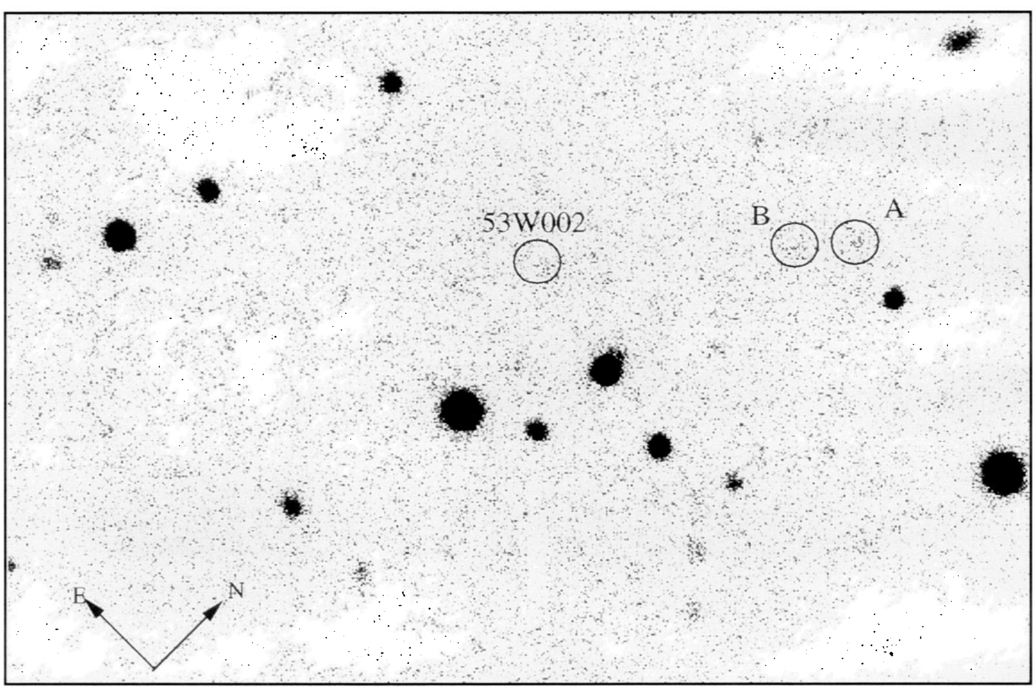

Fig. 3b

FIG. 3.—(*a*) 2 × 3600 s Lyα image of the field near 53W002 taken at the Steward 90 inch telescope through a narrowband redshifted Lyα filter (150 Å FWHM) centered at 4130 Å. (*b*) 720 s broadband Johnson *B* image of the same field. The circled objects are cluster candidates based only on their apparent excess Lyα emission in the upper panel.

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