We present initial results from a redshift survey carried out with the low-resolution imaging spectrograph on the 10 m W. M. Keck Telescope in the Hubble Deep Field. In the redshift distribution of the 140 extragalactic objects in this sample, we find six strong peaks with velocity dispersions of ~400 km s$^{-1}$. The areal density of objects within a particular peak, while it may be nonuniform, does not show evidence for strong central concentration. These peaks have characteristics (velocity dispersions, density enhancements, spacing, and spatial extent) similar to those seen in a comparable redshift survey in a different high Galactic latitude field (Cohen and coworkers), confirming that the structures are generic. They are probably the high-redshift counterparts of huge galaxy structures (“walls”) observed locally.

Subject headings: cosmology: observations — galaxies: distances and redshifts — large-scale structure of universe

1. INTRODUCTION

The Hubble Deep Field (HDF) (Williams et al. 1995) has been surveyed to extraordinary depths, with point-source detection limits around 29 mag in the $V$ and $I$ bands, in an intensive campaign by the Hubble Space Telescope (HST) in 1995 December. The images represent the deepest images ever taken in the optical and have already provided the basis for studies of deep visual counts (Williams et al. 1995), faint object morphology (Abraham et al. 1996), gravitational lensing (Hogg et al. 1996), and high-redshift objects (Steidel et al. 1996; Clements & Couch 1996). These studies represent only the beginning of a large number of scientific projects possible with the HDF data.

In this Letter, we present the first results of a ground-based spectroscopic survey of galaxies in the HDF with the Keck Telescope. These observations were taken in order to provide a database of object redshifts for the use of the astronomical community and in order to expand the faint object redshift surveys of Cowie et al. (1996) and Cohen et al. (1996) to an additional field.

We assume an Einstein–de Sitter universe ($\Omega = 0.5$) with a Hubble constant $100 h$ km s$^{-1}$ Mpc$^{-1}$.

2. REDSHIFT SAMPLE

The HDF was selected on the basis of high Galactic latitude, low extinction, and various positional constraints described by Williams et al. (1996). Redshifts were acquired with the low-resolution imaging spectrograph (LRIS) (Oke et al. 1995) on the 10 m W. M. Keck Telescope over two rectangular strips $2 \times 7.3$ arcmin$^2$ centered on the HDF field in 1996 January, March, and April. One strip was aligned east-west, while the second was aligned at a position angle of 30$^\circ$ in order to maximize the slit length that fell within the HDF itself, where the two strips overlap.

The sample selection is different in each of the two strips. The photometry and the definition of the sample for spectroscopic work are described in Paper II of this series (Cowie et al. 1997). Plans exist to complete the sample in a number of photometric bandpasses, but in view of the great interest in the HDF and the many follow-up studies in progress, we present this data before the complete sample is available.

Table 1 presents the redshifts of 140 extragalactic objects, about half of which are in the HDF itself and the remainder of which in the flanking fields. The median redshift $z$ of the extragalactic objects in the present sample is $z = 0.53$. Only three are quasars or broad-line active galactic nuclei. Twelve Galactic stars were found as well. The radial velocity precision of our redshifts is unusually high for a deep redshift survey. We estimate that the uncertainty in $z$ for those objects with redshifts considered secure and accurate is $\approx 300$ km s$^{-1}$. Coordinates, crude ground-based $R$ magnitudes in a 3$''$ diameter intended for object identification only, and redshifts are given in Table 1.

A more detailed account of the photometric and spectroscopic properties of the entire sample, including photometry from $U$ through $K$, as well as a discussion of incompleteness in the sample selection and redshift identification, is in preparation. These incompletenesses ought not to affect the present work.

3. REDSHIFT DISTRIBUTION

3.1. Velocity Peaks

The redshift histogram over the region $0.2 < z < 0.9$ is shown in Figure 1. It shows clear evidence of clustering. Velocity peaks were identified by choosing bins of variable width and centers in such a way as to maximize their significance relative to occurring by chance in a smoothed velocity distribution (smoothing width 20,000 km s$^{-1}$) derived from the present sample (cf. Cohen et al. 1996). Using this procedure, we isolate six peaks significant at better than 99.5% confidence (see Table 2). The fourth column in Table 2 gives a statistical significance parameter, $X_{\text{max}}$. The fifth and sixth columns give
the comoving transverse size corresponding to 1′ and the comoving radial distance corresponding to $\Delta z = 0.001$. The density in velocity space within these peaks exceeds the average density by a factor that ranges from 4 to as high as 30 for the peak at $z_p = 0.321$. Forty percent of the total sample lies within these peaks. Larger peaks including outliers are also highly significant. The local velocity dispersions for these peaks are strikingly small, ranging from 170 to 600 km s$^{-1}$. These are upper bounds because they are comparable with our measurement errors. They are also similar to the results obtained in a high-latitude field, for which we carried out a deep redshift survey with LRIS earlier (Cohen et al. 1996).

By itself, this sample is too small to measure the two-point correlation function in velocity space. However, there is a 5$\sigma$ excess correlation in the 500–1000 km s$^{-1}$ interval with a correlation scale $r_c \sim 600 \pm 200$ km s$^{-1}$ (cf. Carlberg et al. 1997; Le Fèvre et al. 1996), which can be converted into comoving distance along the line of sight by using the data in the sixth column of Table 2. There is no evidence for correlation with velocity differences in excess of 1000 km s$^{-1}$. No distinction between low and high redshift is discernible. There is no evidence for periodicity in the peak redshifts (cf. Broadhurst et al. 1990).

### 3.2. Morphology Correlation

If we make a simple morphological separation of the galaxies in the redshift survey into spirals, ellipticals, and...
peculiar/mergers, and use the HST images of the HDF and of the flanking fields to classify these galaxies (cf. van den Bergh et al. 1996), then we find there is no indication of any difference in population between the background field galaxies and those in the redshift peaks. In particular, the redshift peaks do not contain a detectable excess of elliptical galaxies.

4. ANGULAR DISTRIBUTION

The angular distribution of the entire sample and of the galaxies in the two most populous velocity peaks is shown in Figure 2. The peculiar shape is caused by the use of two LRIS strips with different position angles. The outline of the area covered is indicated by the solid lines, while the outline of the area of the Wide-Field Camera II observations in the HDF is indicated by the dashed lines. The galaxies associated with the six velocity peaks mostly exhibit a nonuniform distribution, though none show the strong central concentration characteristic of clusters. The redshift sample must be completed before it is possible to make quantitative statements.

4.1. Areal Density

The areal density of galaxies brighter than $0.1L^{*}$ (as defined at $K$) is computed for redshift peaks in the zero-hour field (Cohen et al. 1996) and for the two largest peaks in the HDF, where the $K$ photometry is not fully assembled yet. Corrections have been applied for galaxies below the magnitude cutoff of the survey, assuming a flat luminosity function at the faint end. To investigate a local analog to these structures, this is repeated for the Local Group, for the Virgo Cluster (within a radius of 6$^{\circ}$ from its center) using the survey of Kran-Korteweg (1981), and within the core of the Coma Cluster using data from Thompson & Gregory (1980). In these local structures, the luminosity is determined at $B$ rather than at $K$.

The results are given in Table 3 and suggest that the best local analog is the region of the Virgo Cluster within 6$^{\circ}$ of its center, but although the areal density is a reasonable match, the velocity dispersion in the high-redshift peaks is lower, often significantly lower, than one sees in the central region of the Virgo Cluster.

5. DISCUSSION

5.1. Effects of Sample Definition Decisions

The conclusion of Cohen et al. (1996)—i.e., that a large fraction of the galaxy population at redshifts to unity lie in low velocity dispersion structures—was based on a single field, but the confirmation of strong redshift space clustering in the HDF suggests that the results are generic. The clustering seen here is stronger than that seen in other local and high-redshift surveys (Landy et al. 1996; Le Fèvre et al. 1996). The difference is attributed most importantly to the high sampling density in a small field.

5.2. Structure Morphology

At one level, these peaks may be no more than a manifestation of the fact that galaxies are correlated in both configuration and velocity space. The connection between spatial and velocity correlation functions is quite model dependent (e.g., Brainerd et al. 1996). Conversely, if we can gain an empirical understanding of this relationship, it can discriminate among...
cosmogonic models. We briefly comment upon some possibilities.

One explanation is that the velocity peaks represent structures in velocity space and are not prominent in real space. Such effects are sometimes seen in numerical simulations (e.g., Park & Gott 1991; Bagla & Padmanabhan 1994). For example, they might be a "backside infall" into a large structure in which the Hubble expansion opposes the infall so as to give more or less uniform recession velocity over a large interval of radial distance. The generic kinematic difficulty with this explanation is that in order for features like this not to have many more descendants in which the velocities have long ago crossed, the characteristic lifetimes must be a significant fraction of the age of the universe, which, in turn, limits the mass density contrast to small values. Given that half the galaxies lie in these structures, a large bias parameter must be invoked.

Alternatively, we may be observing structures that are spatially compact and have the shapes of spheres, filaments, or walls. We can argue against these features being clusters on the following grounds: (1) they do not exhibit central concentrations (cf. § 4); (2) the velocity dispersions are too small, 200–600 km s$^{-1}$ as opposed to 600–1200 km s$^{-1}$; (3) the space density of rich clusters is too low—the Palomar Deep Cluster Survey (Postman et al. 1996) finds only seven clusters per square degree out to $z \sim 0.6$ with richness class $\geq 1$; and (4) the redshift peaks do not show the excess of ellipticals characteristic of rich clusters (Dressler 1980).

Small quasi-spherical groups are a possibility. The mean free path is $\sim 100$ h$^{-1}$ comoving megaparsec. The observed structures extend laterally over at least $\sim 6'$ or $\sim 2$ h$^{-1}$ Mpc, implying a space density $\sim 3 \times 10^{-3}$ h$^{-3}$ Mpc$^{-3}$, about one-third the density of $L^*$ galaxies. Alternatively, we can associate the tentative velocity correlation scale of $V_0 \sim 600$ km s$^{-1}$ with a radial extent of $\sim 4$ h$^{-1}$ Mpc and a lateral angular scale of $\sim 12'$ at $z \sim 0.5$.

Filaments and walls have both been described in the theoretical literature (e.g., Bond, Kolman, & Pogosyan 1996; Shandarin et al. 1995). Walls dominate if there is excess power on large scales and they are observed locally (e.g., in the Local Supercluster, de Vaucouleurs 1975; and in local redshift surveys, de Lapparant, Geller, & Huchra 1986; Landy et al. 1996). On this basis, we speculate that the structures we are observing are actually walls.

There are two obvious follow-up investigations that can address this hypothesis. The first is to perform similar redshift surveys in neighboring deep fields. If we assume that the wall normal is inclined at an angle $\theta$ to the line of sight and that the constituent galaxies move with the Hubble flow in two dimensions, then the variation of mean redshift with angular separation of the second survey $\Delta \phi$ and polar angle on the sky $\psi$ is

$$\Delta z = 2[(1 + z)^{3/2} - (1 + z)]\Delta \phi \tan \theta \sin \psi.$$  

For $z = 0.5$, this is $\Delta z \sim 2 \times 10^{-4}$ arcmin$^{-1}$, and in order to see redshift displacements in excess of the velocity dispersion the additional surveys must be displaced by $\sim 20'$. With several lines of sight, it might be possible to test the above relation.

The second approach is to look for morphological and luminosity function differences between the galaxies within and outside the velocity peaks using wide-field, multiband photometric surveys to the depth of the redshift survey. Both investigations are underway.

We thank the Hubble Deep Field team, led by Bob Williams, for planning, taking, reducing, and making public the HDF images. We are grateful to George Djorgovski, Keith Matthews, Gerry Neugebauer, Paddy Padmanabhan, Mike Pahre, Tom Soifer, and Jim Westphal for helpful conversations. The entire Keck user community owes a huge debt to Bev Oke, Jerry Nelson, Gerry Smith, and many other people who have worked to make the Keck Telescope a reality. We are grateful to the W. M. Keck Foundation, and particularly its president, Howard Keck, for the vision to fund the construction of the W. M. Keck Observatory. Support by NASA and the NSF is greatly appreciated.
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