Visualizing the Universe

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Abstract

These decades are the first in which we can begin to map the universe. Recent surveys reveal patterns in the distribution of galaxies — patterns coherent on scales of 150 million light years or more. These patterns contrast with the smoothness of the radiation background measured by the COBE satellite. Together these observations challenge our understanding of the origin of galaxies — structure — in the universe.

"Visualizing the universe" is crucial for exploring the 3-dimensional map, for analyzing it, for designing instruments to make deeper maps with new large telescopes, and for sharing the excitement of discovery with the public.

1 Introduction

Because we are just beginning to map the universe, we are still asking basic questions. How does the universe look today? What are the initial conditions for galaxy formation and how did structure evolve?

The foundation for modern maps of the universe is Hubble's 1929 [1] discovery that the universe expands according to the law

$$v_H = H_o R$$

where v_H is the apparent recession velocity of a galaxy, R is its distance, and H_o is the Hubble "constant." Cosmological distances are quoted in megaparsecs (1 Mpc = 3.26×10^6 light years). Because the value of H_o is uncertain by at least a factor of 2, we write $H_o = 100h$ km/s/Mpc where h is between 0.5 and 1. Here we take h=1 unless otherwise specified.

We measure the line-of-sight recession velocities of galaxies by identifying absorption and/or emission lines in their spectra; we measure the shift of these features from the laboratory (rest) wavelength toward (generally) longer — redder — wavelengths. This *redshift* is related to the apparent recession velocity by:

$$z = \Delta\lambda/\lambda_r \simeq v/c$$

where $\Delta\lambda = \lambda_o - \lambda_r$ is the shift of a feature from its rest (laboratory) wavelength, λ_r to the longer observed wavelength λ_o. With the two angular positions of a galaxy on the sky and a measurement of its redshift, we can place each galaxy in a three-dimensional (3-D) map of the universe.

We call the 3-D space for our map *redshift space*. In the simplest approximation, a measurement of redshift is a measurement of the distance to a galaxy and thus a map in redshift space is a map in real 3-D position space. However, "peculiar" velocities originating from the motions of galaxies in clusters and from gravitationally driven large-scale flows complicate the interpretation of the redshift. Because these "peculiar" velocities are small compared with the scale of large structures in our maps, we ignore them for this discussion. We take the maps in redshift space as first pictures of our local region of the universe (i.e. we take $v \sim v_H$).

A revolution in detector technology has made ours the age of mapping the universe. Between 1929 and the late 1970's, the transition from photographic plates to electronic detectors reduced the telescope time required to measure the redshift of a single galaxy by a factor of ~50. Between 1976 and 1990, the number of galaxies with measured redshifts has risen steeply from 2,700 to more than 50,000. A field once data poor is becoming data rich. Fiber optic instruments (see below) promise an additional hundredfold increase in the efficiency of measuring redshifts!

We have now mapped about 10^{-5} of the volume of the visible universe — about the fraction of the earth

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covered by the state of Rhode Island. Although the coverage is small, the map contains surprises. The patterns in the distribution of galaxies are more coherent and larger than most of us had expected. All recent surveys give the same message: large structures are a *common* feature of the galaxy distribution.

The new data are changing our perception of the universe. The 3-D data demand new tools. Visualization techniques are important for exploring and analyzing the data, for comparing the data with models, and for "designing the future." Computer animation of the data has been a way of bringing these new maps before the public.

The mapping project at the Harvard-Smithsonian Center for Astrophysics (CfA) — the CfA Redshift Survey — is one of the largest nearing completion. John Huchra (CfA) and Margaret Geller (CfA) are the principal investigators. Dan Fabricant (CfA) is the instrument designer. Mark Bajuk (National Center for Supercomputing Applications, University of Illinois), Emilio Falco (CfA), Michael Kurtz (CfA), and Alberto Accomazzi (CfA) are responsible for visualization of the redshift survey — from laser printer plots to virtual reality. Boyd Estus (Heliotrope Studios Ltd.) is the director of the films designed to invite the public to share the experience of doing science.

2 The Maps and the Questions

When we ask how the universe looks today, we ask how galaxies like the Milky Way are arranged on large scales. We assume that galaxies are tracers of the distribution of matter in the universe.

One of the fundamental ideas of modern cosmology is enshrined as the cosmological principle: the universe is homogeneous and isotropic. But ... what is the scale of homogeneity? How large a piece of the universe must we survey in order that one survey is statistically equivalent to another? What is the appropriate description of the structure? We may be close to answering these questions, but we have thought we were close before.

For a long time, many thought that the largest scale of inhomogeneity was $\sim$10 Mpc. But then, in 1981, Kirshner, Oemler, Schechter and Shectman [2] discovered the void in Boötes, a region with a diameter of 60 Mpc where the density of bright galaxies is $\lesssim$20% of the global mean. Low density regions of this scale were unexpected and the discovery created a stir.

In 1986 the first slice of the CfA redshift survey [3] and a survey of the Perseus-Pisces region by Giovanelli and Haynes [4] indicated that low density regions like the Boötes void were, in fact, a *common* feature of the large-scale galaxy distribution. The first CfA slice is part of a project to measure redshifts for nearby galaxies in a magnitude (flux) limited sample and will include some 15,000 galaxies.

We carry out the survey with a strategy designed to uncover large-scale coherent patterns without having to wait for completion of the entire survey. We measure redshifts for galaxies in "slices" at constant declination (celestial latitude) which span the full right ascension (longitude) range of the catalogue of galaxies (this range is limited by obscuration within our own Galaxy). Figure 1 shows the first slice. Nearly all of the 1074 galaxies in the slice lie in extended thin structures. The boundaries of the low density voids (regions containing very few galaxies) are remarkably sharp. The separation of galaxies in the structures is generally small compared with the radius of the void. The largest void has a diameter of some 50 Mpc, comparable with the void in Boötes.

Based on the appearance of this slice and the distribution of galaxies on the sky (there is no structure visible on the sky), we suggested that galaxies are arranged on thin two-dimensional (2-D) surfaces which surround (or nearly surround) the voids. At this first stage of the survey, simple 2-D displays like Figure 1 were adequate.

Completion of three more slices confirmed the suggestion of 2-D structures (see Figure 3) [5]. In all four slices a thin structure runs across the entire survey; this structure is known as the "Great Wall." The extent of the Great Wall is limited only by the boundaries of the map. Although the display in Figure 3 gives some impression of the coherence of the structure, only real-time 3-D displays and/or animated displays show how thin and well-defined the Wall is.

Large-scale inhomogeneities like the Great Wall imply that the CfA survey is not yet a sample large enough to determine the *typical* properties of the distribution of galaxies. Both large voids and sheets are common features of the distribution of galaxies. The currently preferred model — cold dark matter with biased galaxy formation — produces less structure on scales $\gtrsim$ 10 Mpc than we observe [6]. The differences are qualitatively evident in real-time 3-D displays, but much less so in 2-D projections.

Preliminary analyses of deeper maps (to fainter flux limits, larger redshifts) paint a confusing picture. Three surveys with different observing strategies lead to qualitatively different conclusions about structure on the largest scales. Broadhurst *et al.* [7] measured redshifts for galaxies in a deep narrow cone. They found structure on a scale of 126 Mpc. Preliminary analyses of two surveys (the Las Campanas [8] and Century [9] surveys) which cover shallower regions over a larger solid angle do not seem to confirm this particular scale. Shectman *et al.* (Las Campanas) claim there are no structures larger than those already seen in the CfA survey. In contrast, the Century Survey indicates that there are larger scale variations, but not with the particular scale observed by Broadhurst *et al.* .

The short story is that we still do not know the scale of the largest inhomogeneities in the distribution of galaxies. However, the rate of data acquisition continues to increase as new fiber instruments come on line. Visualizing maps containing 100,000 or even a million galaxies will require fast machines and clever techniques.

New instruments on large (6.5 meters or more) telescopes hold an exciting promise for the future: direct observation of the evolution of the structure. As we look to larger and larger redshifts, we look back to earlier epochs. Presumably, over the next few years we will have a description of the nearby structure. This description will provide the standard for comparison with the deeper surveys.

3 Displaying and Analyzing the Maps

As redshifts began arriving in larger and larger numbers, we were quickly confronted with the interpretation of structures that had never been seen. In our initial attempts, we tried to apply techniques known to us from astronomy and from image processing. But, we soon realized that visualizing complex data structures was more of an *art*, which has only recently started to evolve into the *science* of visualization.

The first step we recognized as crucial was the transition from 2-D representations of redshift data, such as that of Figure 1, to a 3-D view (unfortunately, still projected onto two dimensions), as shown in Figure 2. Figures 1 and 2 depict a "slice" of the universe out to a radial distance of about 150 Mpc, with opening angles of about 120° and 6° in right ascension and declination, respectively. Figure 1 is a 2-D plot, with no 3-D information. Figure 2 is a projection from three dimensions onto a plane, which includes 3-D cues due to perspective. Few 3-D hints are apparent with the number of galaxies in a single slice (about 1000). However, we expected that an ability to rotate the slice would help us visualize and better understand the structure, especially as the number of galaxies and slices grew.

The lack of a large budget, and the existence of the Image Processing Laboratory at CfA prompted us to utilize their IIS and its replacement, a Gould-deAnza processor, to render slices. The basic design problem was solved by representing each galaxy as a limb-darkened sphere (a gaussian brightness profile). The structure could be rotated once the software was written, in-house. Although the concept was straightforward, its implementation, which ran on one of the first MicroVAX II computers at CfA, was (in retrospect) painfully slow. Thus, real-time motion of the structures remained a fond hope. Nevertheless, we were able to produce motion on 16mm film that now appears primitive, but which was a significant advance six years ago. Furthermore, the same software was also later applied to the rendering of simulations of planetary collisions.

The subsequent arrival of a VAXStation 8000 (Lynx), a donation from Digital Equipment Corporation to the Large Scale Structure group at CfA, rekindled our hopes for real-time, 3-D motion. The Lynx was a prototype, a sort of "idiot savant" of the computing world, which is able to display 3-D graphics at great rates of vector and polygon display, comparable to those of current workstations, but little else, with limited memory capacity and software. In fact, R. McMahan and E. Falco managed to modify demo software that accompanied the machine, to display the first slice, and additional slices (up to six can be accomodated in graphics memory). The basic design problem of rendering individual galaxies was reconsidered, and solved anew by representing them as dandelion-like bundles of several rays. Seen from a distance, such representations emulate the limb-darkening of our early attempts.

Although the Lynx is well-designed for applications such as CAD, where a relatively small number of surfaces may suffice to represent objects, its limited memory dictated the chosen simple representation for our galaxies. We had now achieved real-time, under control of intuitive and interactive knobs. The main goal of visualization of the large-scale structures was reached. However, as the number of slices available grew to four, real-time was not quite achievable, but nearly so. We were now able to record sequences under control of the Lynx, directly to video, with the help of a high-quality YEM scan converter. We managed to record frames at about one-quarter of video rates, a speed that could be compensated for during video editing. Thus, we were able to produce the short video

Where the Galaxies Are, which has achieved very wide distribution and recognition (distributed by the Astronomical Society of the Pacific, 390 Ashton Ave, San Francisco, CA 94112, tel. 415 337-1100).

Figure 3 shows a typical 3-D view of four slices (with about 4000 galaxies), one of thousands of images that we created with the Lynx. Note the high significance of the structures evident in this image, features that cannot be revealed without a 3-D representation, which is assisted by the use of colors (but not by subtler features such as depth cueing, which could not be used with the representation chosen for the galaxies). A much deeper understanding of the properties of the structures, such as the sharpness of the boundaries of the Great Wall (see Section 2), can only be attained with the help of motion in three dimensions.

Over the past eighteen months, we developed a very unique and fruitful collaboration with the Visualization Group at the National Center for Supercomputing Applications (NCSA) at the University of Illinois. Our first visualization results captured their attention, and we managed to collaborate in the production of a much more sophisticated representation of our redshift surveys. One of our ambitions that could not be achieved with the Lynx was to represent galaxies in a realistic fashion. Galaxies are not, after all, fuzzy balls, but come in many different sizes, shapes and colors. The main distinction that we wished to reveal was that between spiral and elliptical galaxies, because the morphology of galaxies is related to their environment: spirals are sprinkled relatively evenly, whereas ellipticals become more plentiful in the cores of clusters of galaxies. NCSA provided state-of-the-art hardware (from SGI workstations to Crays), software (such as Wavefront products), and staff who provided great impetus (especially through Mark Bajuk) for our visualization project.

Since the components to produce the motion were available (but subsequently required a significant effort and the expertise of NCSA staff to choreograph motions), we once again turned to the basic design problem, the representation of galaxies. We provided images of several spiral and elliptical galaxies that were taken by Steve Kent at the Smithsonian's Whipple Observatory with a 60-inch telescope. The images were recorded with a CCD detector; we delivered them to NCSA as FITS image files (a standard astronomical format), on tapes. The first step was to "colorize," simply by assigning false, but relevant colors to each galaxy (bluer spirals, yellower ellipticals), in proportion to its brightness. The colorization was performed on Macintosh computers, with Adobe Photoshop, and the color information was recorded in a format that could next be read by Wavefront software on SGI workstations. Our goal was to literally navigate the redshift survey, which meant that 2-D, zero-thickness galaxies would not do. We solved this problem in two ways, depending on whether a galaxy's type was spiral or elliptical. For spirals, the solution was to "warp" the flat CCD colorized images as texture maps, onto polygonal objects that were nearly flat, but with finite thickness and with a bulge at their centers, as spirals are known to be. For ellipticals, a simpler type of body, the solution was to always present a face-on view of each galaxy, regardless of the state of overall rotation of the observer relative to the galaxies, to yield the illusion of three-dimensionality. In the latter case, rather complicated relations between rotation matrices were worked out at NCSA. The handful of galaxy images that we chose became the full population in our survey, simply by assigning random orientations and a range of sizes to the galaxies, and by selecting appropriate fractions of spiral and elliptical galaxies.

The motions were choreographed in wire-frame mode with Wavefront software, and then rendered. The amount of time required per frame amounted to up to 40 minutes, depending on the point of view. Thousands of frames were thus rendered, with the help of multiprocessor-equipped SGI workstations, and could be viewed after recording on Abekas digital editing equipment. Finally, the rendered frames were recorded in video format for initial viewing. Rendering was later performed at film resolution. The resulting files were transported on tape to CfA, where over the past few months we recorded them on 16mm color film, with a Matrix QCR-Z digital recorder (which itself presented many obstinate, but now tamed, obstacles). The results have been extremely pleasing and rewarding. Since galaxies are represented by objects that are about ten times larger than real galaxies would be, the large-scale structures make an extremely vivid impression on the viewer. Thus, by concentrating on a realistic representation of galaxies, a useful side effect was to enhance the perception of sheets and voids in the distribution of galaxies. Figures 4 and 5 show two different views of the redshift survey that were produced as just described. The view is nearly face-on for the nearest slice in Figure 4, and from within the slices in Figure 5. Unfortunately, again only motion can reveal the true significance of these representations of our data.

An interesting point can be made in terms of costs of production of visualizations of the CfA redshift survey. We began with 2-D views, which could be produced on equipment costing a few times $ 1,000. Upon transition to three dimensions, we jumped to equipment costing several times $ 100,000; as technology progressed, and visualization became more sophisticated, we fell back to equipment costing several times $ 10,000 (per unit). Future techniques, such as that of virtual reality (which is under experiment at NCSA, with the CfA redshift survey), are so incipient that their real cost and promise are yet to be revealed.

4 Instruments for the Future

Future large redshift surveys at the CfA will be carried out with a new multiobject spectrograph that is currently being designed. In the tradition of somewhat silly names for astronomical instruments, we have named this new spectrograph the Hectospec. The instrument will be placed at the focus of the Multiple Mirror Telescope (MMT) after it has been converted to use a single 6.5m mirror. The converted MMT will have a very large field of view, subtending 1° on the sky, approximately two moon diameters. This very large field will contain over a thousand galaxies bright enough to study with the MMT irrespective of the direction the telescope is pointed.

The Hectospec will use 300 optical fibers to intercept the light from the images of these galaxies at the MMT focal surface, and carry it to a large spectrograph mounted on an optical bench at the back of the telescope chamber. Each optical fiber is terminated in a button containing a magnet and a tiny prism. The prism allows the optical fiber which lies along the focal surface to look up at the galaxy images. The magnet holds the fiber down temporarily to the focal surface for the duration of an observation, yet allows the configuration of the fibers to be easily changed. Figure 6 shows the the optical fibers deployed on a simulated field of galaxies. A pair of fiber-gripping robots mounted above the focal surface is responsible for moving the fibers to new configurations.

Instruments similar in concept to the Hectospec are currently in use at a number of major observatories. The Hectospec differs in that it contains a greater number of fibers and that we are demanding greater speed in moving between different configurations. Furthermore, the Hectospec's designer is adverse to receiving trouble reports in the middle of the night, so we are hoping to achieve a very high degree of reliability.

The design of the Hectospec must allow the free movement of the robotic positioners and a clean routing of the optical fibers through and out of the instrument. Given that we must keep track of a large number of moving parts, we have made extensive use of computer visualization techniques; essentially all of the design has been carried out on the computer. Because the instrument structure must perform to very high standards as the instrument is rotated about the optical axis of the telescope and oriented in different positions with respect to gravity, the exchange of information between the CAD visualization tools and the finite element analysis code is important. Edward Hertz, our project engineer, and Robert Fata, our structural engineer, have been using I-DEAS software (a product of Structural Dynamics Research Corporation) running on Silicon Graphics Personal Iris workstations. None of us can imagine enjoying the design process or carrying it out effectively without these tools.

Our design process differs from that of some industrial equipment where extensive prototyping and design iteration are possible. The extremely specialized nature of our instruments and limited budgets demands a great deal from the initial design process. We have to get things right in one cycle. Our hope is that careful use of the CAD tools will eliminate unwelcome surprises. We are glad to be surprised about the universe, but not by our instrumentation.

5 Showing the Maps to the Public

In addition to its impact on a broad scientific community, the CfA survey has attracted public interest. A short video, *Where the Galaxies Are*, which explains and displays the 3-D map is on display at the National Air and Space Museum, the Deutsches Museum, the Franklin Institute and elsewhere. The graphic display is perhaps one of the examples of scientific visualization most widely seen by the public. We estimate that the graphics have been included in broadcasts seen by about 100 million people.

Public audiences are curious about the results and the process of science. People are eager for access. Part of the problem of public science education is a lack of visually appealing, exciting material which takes non-scientists to the forefront of scientific research.

State-of-the-art graphics provide a way of introducing people to the frequently foreign worlds of science — from subatomic particles to the cosmos. One need only look to Hollywood to see the remarkable impact of skillful graphics. Talk about *2001, Star Wars, Total Recall* or *Terminator 2*. People remember the graphics in detail.

In contrast, few remember the graphics segments in a *Nova* program. Why? Good graphics are expensive. The budgets for science programs frequently restrict the production team to taking what is readily available from working scientists. These graphics are generally too abstract to be grasped readily by the non-scientist.

Design of graphics for public education in science requires the participation of scientists, graphic artists, and filmmakers. There are many technical and artistic challenges along the way. Recently, with the support of NCSA (see Section 3), a group of us worked together to animate the CfA redshift survey using real galaxy images. This animation (on 16-mm film and on videotape) has a much more powerful impact than the display of points in our first video. People seem to feel that they are actually voyaging through the universe — and unlike *Star Wars* our images are the real thing! This animation is an integral part of a 40-minute film, *So Many Galaxies ... so Little Time,* which shows how a scientific group works. The graphics will also be available separately in a 5-minute video, *The Galaxy Trip.*

The first step in a scientific visualization for public display is to extract the essential ingredients of the result. The graphic design should make these elements visually obvious using symbols — not labels — which are easily recognizable. Most people will see the graphics on television. The original graphics should be sufficiently clear and sharp for them to have a visual impact even after the degradation to TV broadcast standards.

Often real images, galaxy images, are attractive on their own. They also present problems. In our case the challenge was to make a convincingly 3-D display based on 2-D galaxy images. We invented the necessary tricks.

Scientists rarely think about the emotional content of the graphics they use every day, but for public display both the intellectual and emotional content are important. To gauge the impact, we used a real-time 3-D graphics system. By "playing" with the data in a simple representation (points for galaxies) we were able to choose points of view and camera moves for the NCSA-rendered graphics which draw people into the universe. In a sense, the enormous scale of patterns in the universe – hundreds of millions of light years – defies human imagination. Part of the magic of science is that we can represent a piece of the universe so that we feel we know it. One would, of course, apply similar arguments to other realms of science like the world of subatomic particles.

Once we have drawn people into our world, we travel through it. The trip is a sort of reward for understanding. We couch the trip through this strange space — the universe — in the familiar terms of the flight path of an airplane. The familiar in the unfamiliar gives the audience the kinesthetic sense of a real experience they understand. Interestingly, the application of actual flight paths from W.W. II fighter footage was one of the innovations which made *Star Wars* so effective.

We chose a path through the universe which gives the viewer an appreciation for the spaces. We show the contrast between voids and dense regions and give the viewer a feeling for these patterns — the largest ones we know. The emotional reward of the trip is enhanced by appropriate choices of the focal length of the lens. A wide angle enhances the impression of a vast surrounding space.

Acknowledgments

Our collaboration with Mark Bajuk, a graphic designer at NCSA, was unusual but could be a model for collaborations which cross the lines between science and art. Firms involved in the production of graphics hardware and software could, as NCSA did, provide technical support and free use of equipment. The scientific/technical community could make an important contribution to public education in science by encouraging and providing technical and financial support for these efforts. We gratefully acknowledge the support of the Smithsonian Institution, NASA, Digital Equipment Corporation, NCSA, TASC, JPL and the Dodge Foundation.

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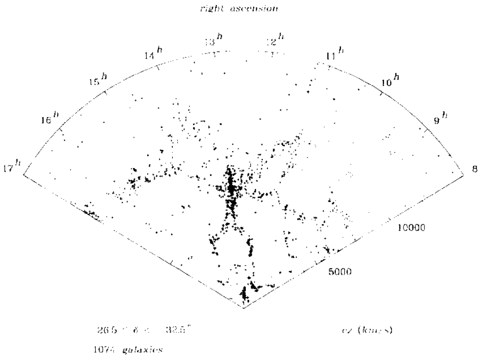

Figure 1: 2-D laser printer plot of our first slice of the universe.

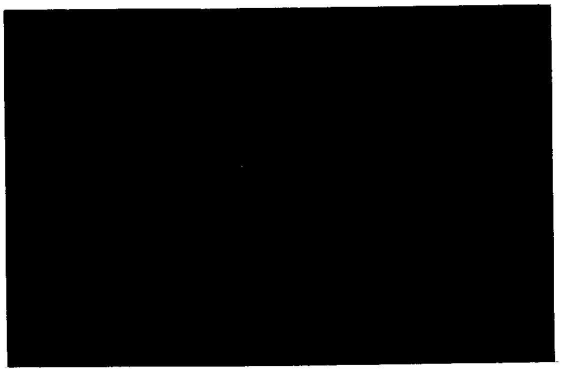

Figure 2: First slice, rendered on a MicroVAX II and displayed with a Gould-deAnza image processor.

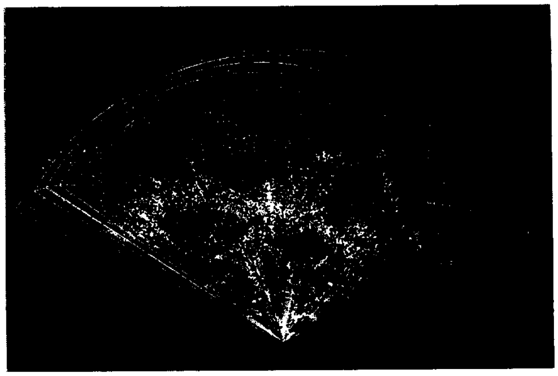

Figure 3: Projection of a 3-D view of four slices, rendered and displayed with a VAXStation 8000 Lynx.

Figure 4: Projection of a 3-D view of six slices, rendered with SGI workstations at NCSA.

Figure 5: NCSA graphics from within the slices, showing individual galaxies, voids, and sheets.

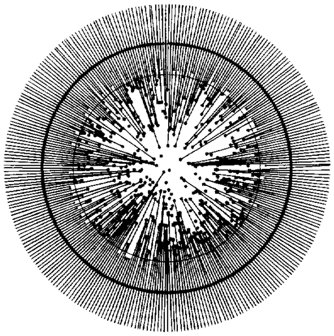

Figure 6: The Hectospec's 300 optical fibers, deployed on a simulated field of 500 galaxies.

(See color plates, p. CP-39.)