The NOAO Deep Wide-Field Survey

Buell T. Jannuzi and Arjun Dey

National Optical Astronomy Observatories, 950 N. Cherry Avenue, Tucson, AZ 85719

Abstract. The NOAO Deep Wide-Field Survey is a deep optical and IR ($B_W RIJHK$) imaging survey of 18 $\square^\circ$ of the sky with the primary goal of studying the evolution of large-scale structure from $z \sim 1-4$. The images should also enable investigation of the formation and evolution of the red-envelope galaxy population and the detection of luminous, very distant ($z > 4$), star-forming galaxies and quasars. We are mapping an unprecedentedly large area to faint flux limits ($B_W RI \geq 26$ AB mag. and $J, H = 21; K = 21.4$ AB mag. 5-σ detection limits in a $2''$ diameter aperture). This survey will also be valuable in addressing many other astrophysical problems, and we have designed its execution in a manner that attempts to maximize the scientific return when it becomes a publicly available database.

1. Survey Goals

We have just completed the first two years of observations for a deep wide-field optical and IR imaging survey designed to investigate the extent, nature, and evolution of large scale structure at redshifts $z \approx 1-4$; to identify luminous $z \gtrsim 4$ star-forming galaxies; and to find the cosmologically important $z > 1$ red-envelope galaxy population (e.g., old ellipticals and dusty protogalaxies). While there are tantalizing hints of small-scale clustering in the $z > 2.5$ starburst population (e.g., Steidel et al. 1996), the detection of large-scale structures at $z > 1$ will provide unique constraints on hierarchical clustering theories and galaxy formation models. In addition, there is growing evidence that massive elliptical galaxies form first at $z > 4$ (in apparent contradiction to hierarchical scenarios) and are already old (>4 Gyr) at $z > 1.5$, providing a strong lower bound to the age of the Universe (e.g., Dunlop et al. 1996, Spinrad et al. 1997, Francis et al. 1997). Our survey will probe the evolution of the large scale clustering properties of the $z > 1$ galaxy population, is designed (with an IR component) to identify the $z \sim 1$ luminous red galaxy population, and will trace the evolution of luminous star-forming galaxies to $z \sim 5$. The survey occupies a unique region of parameter space (Figure 1), providing both optical and IR coverage over a large area and to great depth in the optical bands.

In addition to meeting our primary scientific goals, the calibrated survey data and object catalogues will also meet the scientific needs of a broad range of other programs (including proper motion surveys for brown and white dwarfs, using our survey as one of several epochs of observation; ambitious spectroscopic

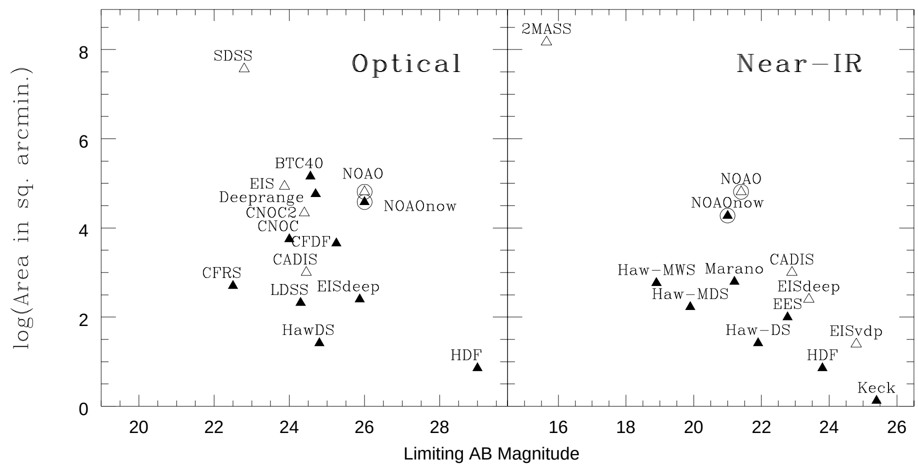

Figure 1. A comparison of the NOAO Survey with selected recent and proposed surveys of the sky. Optical surveys are shown in the left panel and near-IR surveys are shown in the right. The survey detection thresholds (in a $2''$ dia. apt.; AB units) shown are for the deepest band, which provides a comparison for the surveys' sensitivities to a flat-spectrum star-forming galaxy. Completed surveys are represented by filled triangles and those planned or in progress by open symbols. Of the many Hawaii K-band surveys, three representative ones are plotted. The pioneering LDSS, AutoFib, CFRS and Hawaii surveys all cover areas of $< 600\Box'$ and were generally limited to magnitudes brighter than $B = 24$. The majority of the Sloan DSS will be limited to $R = 23$ and the 2MASS survey is limited to $K = 13$ (10σ) for galaxies. The points labeled "NOAOnow" represent the status of the NOAO Survey through the end of our Semester 1998B observations (only showing the R-band and K-band data at this point, although some B_W and I-band data have been obtained).

redshift surveys with the 8m class telescopes; studies of our Galactic halo; and weak-lensing studies to map the mass distribution of the Universe).

2. Survey Design

We are observing two independent 9 $\Box^\circ$ fields, selected for their low IRAS cirrus emission, low $N_{\rm HI}$, lack of very bright stars, and the availability of radio data from the VLA FIRST Survey for these fields. Both fields have $f_{100\mu m} <$ 1.4MJy/sr, $N_{\rm HI} \lesssim 1.75\times10^{20}{\rm cm}^{-2}$, corresponding to $E(B{-}V)$<0.04. The northern field is $3^\circ\times3^\circ$ centered at (J2000) RA =14:32:06, DEC =+34:16:48 and the southern field is $2^\circ\times4.5^\circ$ centered at (J2000) RA =02:10:00, $DEC = -04$:30:00.

The optical imaging is currently being done with the new MOSAIC cameras on NOAO's 4m telescopes. At the KPNO 4m each individual image covers a

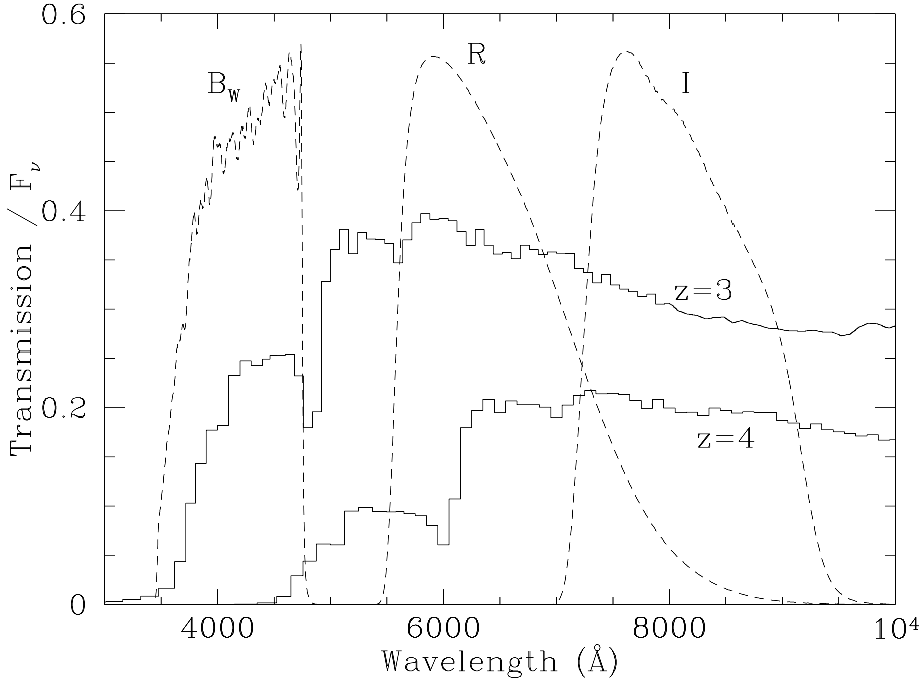

Figure 2. The optical filters used in the NOAO Deep Wide-Field Survey, shown superimposed on the spectra of $z = 3$ and $z = 4$ star-forming galaxies. The galaxy spectra have been constructed from a redshifted Bruzual-Charlot model spectral energy distribution, with the intervening cosmic absorption for wavelengths less than 1216 Å estimated using Madau et al. (1996) approximation. The filter transmission includes the quantum efficiency of the MOSAIC CCDs and the throughput of the CTIO prime focus corrector. The KPNO 4m PF corrector has slightly higher transmission efficiency.

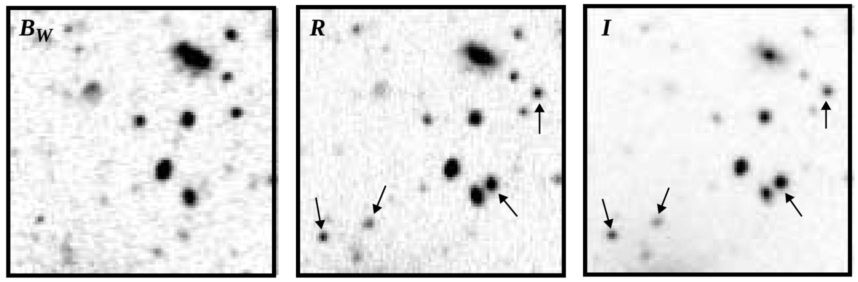

Figure 3. Shown in these panels is a $40'' \times 40''$ sub-region of our survey (approximately $0.5h_{50}$ Mpc on a side for $z \sim 3$) in which several candidate high redshift objects (B_W-"drop-outs") can be seen.

$36' \times 36'$ field. The optical filters being used are from the Kitt Peak Harris set with the exception of the custom B_W filter (see Figure 2). The IR imaging is being done with the Ohio State/NOAO Imaging Spectrograph (ONIS) at the KPNO 2.1m. Using a 2-quadrant InSb detector this imager provides a $2.9' \times 5.8'$ field of view.

At $B < 24$, galaxy number counts are dominated by low-z (<1) starbursting dwarfs; luminous galaxies at $z > 1$ only dominate at fainter magnitudes (Cowie et al. 1996). Any attempt to study the evolution of the high-z galaxy population must therefore begin with a survey that reaches well beyond the depths probed by recent wide-field surveys (Table 1). The successes in detecting $z > 3$ galaxies by their Lyman break (Steidel et al. 1996; Madau et al. 1996) suggest that this method can be extended to higher redshifts by looking for 'B-band dropouts'. Our initial data demonstrates that we are able to find such candidate objects (Figure 3). Our optical detection limits ensure identification of the $> L^*$ star-forming galaxy population at $z \gtrsim 3.5$. The IR component of the survey is critical to the identification of the old, high-z (>1) elliptical galaxy population (missed by current optical surveys; e.g. Hu & Ridgway 1994, Graham & Dey 1996), and to the discrimination against low-z contamination in our search for 'B-band dropouts' (see Fig. 4). The IR limits allow the detection of the entire (passively?) evolving $L \geq L^*$ elliptical galaxy population out to $z \lesssim 2$ ($K = 21.2$ AB mag. for a $z = 1.5$ *unevolved* $M_B = -21$ elliptical; $H_0 = 65$, $q_0 = 0.1$). The planned depth should also permit the study of the Galactic halo stellar populations, the coolest high-latitude white dwarfs to 1.5kpc, young (bright) field brown dwarfs (like GL229B) to about 75pc, distant supernovae, and distant radio sources.

The large areal coverage of the survey ($2\times9\Box°$) is critical to the realization of many of our scientific goals. It allows the detection of large scale structure in the forming galaxy population at early epochs and the study of the passively–evolving red–envelope galaxy population at $z > 1$. The redshift distributions of galaxies are clustered to $z \sim 1$, with measured σ_v of coherent structures comparable to that of the Great Wall (Cohen et al. 1996a, 1996b). Large scale clustering in the metal–line and high column density absorption line systems has been reported (e.g. Jakobsen et al. 1986, Sargent & Steidel 1987, Bahcall et al. 1996, Jannuzi 1998) at $z \sim 2 - 4$. A $3° \times 3°$ survey area corresponds

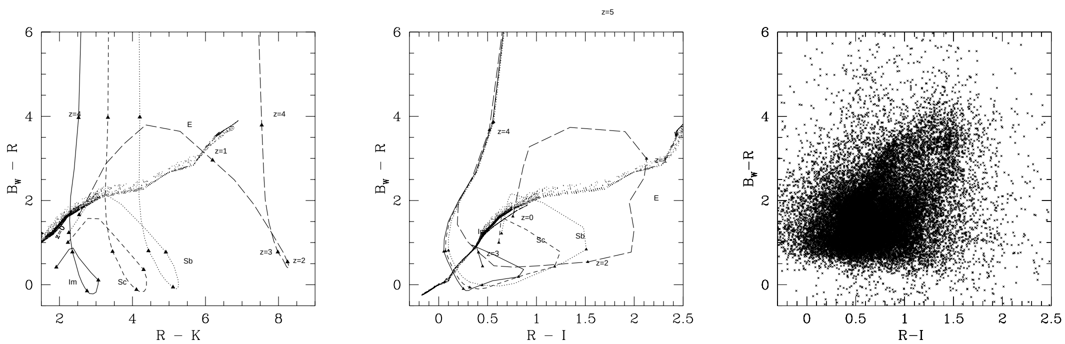

Figure 4. The identification of high-z galaxies in the B_WRI and B_WRK color-color planes for different (unevolving) galaxy types (solid: Im; short dashed: Sc; dotted: Sb; long dashed: E). The solid triangles are spaced at unit redshift intervals (z=0,1,2,3,4). Intergalactic HI absorption was modeled using the Madau et al. 1996 approximation. The expected locations of stars in the color planes are shown with small points. The $R-K$ color selection clearly separates out the $z > 1$ elliptical galaxy population, and the $1 < z < 2$ red and blue galaxies are unambiguously identified in the lower part of the B_WRK color-color diagram. Objects at $z > 4$ are identifiable. The final six-band data set should yield accurate photometric redshifts (e.g. Connolly et al. 1995). The panel at right is a color-color plot constructed from a portion ($< 0.2\Box^\circ$) of the survey data. Objects detected in all the optical bands are shown (i.e. candidate "drop-outs" are not included in this plot).

to $\approx 94 \times 94$ Mpc^2 at $z \sim 2$ ($H_0 = 65$, $q_0 = 0.1$), which will allow us to well–sample the cluster-cluster correlation length and connect it with shallower (low-z) wide-field surveys (e.g., $16\Box^\circ$ Postman et al. 1998 $I_{5\sigma} = 23.7$; i.e., to $z \sim 1$). In addition, the large area of the survey allows us to find rare objects. An example are luminous galaxies at high-z (red, gEs at $z > 1.5$ and luminous forming galaxies at $z > 4$), which are rare enough (e.g., there are no $L \geq L^*$ $z > 4$ candidates in the HDF) that large areal coverage is required to find them. Finally, since our fields lie within completed FIRST survey (Becker, White, & Helfand 1995) regions, we will identify almost all the radio sources in these regions ($\sim 90/\Box^\circ$ with $S_{20cm} > 1$mJy) and produce a large sample of faint high-z radio-loud QSOs candidates. The $18\Box^\circ$ area should yield $\sim$100 $4 < z < 5$ radio-quiet QSOs and the IR observations will allow us to search for the elusive red QSO population (Webster et al. 1995) and characterize their space density.

Acknowledgments. BTJ thanks the organizers for hosting a wonderfully informative and enjoyable workshop. We acknowledge support from the National Science Foundation through its funding of the National Optical Astronomy Observatories through a cooperative agreement with the AURA, Inc.. We thank all of our Co-I's on this project for their continuing efforts on this survey and in particular Ian Del'Antonio, Tod Lauer, James Rhoads, Frank Valdes, and Ted von Hippel for assistance with material presented in the figures of this contribution. Further details about the survey are at http://www.noao.edu/noao/noaodeep/.

Table 1. Survey Detection Limits

Observed Band	5-σ Detection in 2″ dia. apt.		1-σ surface brightness limit per □″	
	AB mag.	Vega-mag.	AB mag.	Vega-mag.
B_W	26.6	26.6	29.0	29.0
R	26.0	25.8	28.4	28.2
I	26.0	25.5	28.4	27.9
J	21.0	20.2	23.4	22.6
H	21.0	19.6	23.4	22.0
K	21.4	19.5	23.8	21.9

References

Bahcall, J. et al. 1996, ApJ, 457, 19

Becker, R. H., White, R. L. & Helfand, D. J. 1995, ApJ, 450, 559

Cohen, J. et al., 1996a, ApJ, 462, L9

Cohen, J. et al., 1996b, ApJ, 471, L5

Connolly, A. J. et al., 1995, AJ, 110, 2655

Cowie, L., Songaila, A., Hu, E. & Cohen, J. 1996, AJ, 112, 839

Dunlop, J. et al., 1996, Nature, 381, 581

Francis, P. J., Woodgate, B. E. & Danks, A. C., 1997, ApJ, 482, L25

Graham, J. R. & Dey, A. 1996, ApJ, 471, 720

Hu, E. & Ridgway, S. E. 1994, AJ, 107, 1303

Jakobsen, P. et al., 1986, ApJ, 303, L27

Jannuzi, B. T. 1998, in Proceedings of the 13th IAP Astrophy. Colloq., eds. P. Petitjean & S. Charlot, (Editions Frontieréres: Paris) p. 93

Madau, P. et al., 1996, MNRAS, 283, 1388

Postman, M., Lauer, T., Szapudi, I., & Oegerle, W. 1998, ApJ, 506, 33

Sargent, W. L. W. & Steidel, C. C. 1987, ApJ, 322, 142

Spinrad, H. et al., 1997, ApJ, 484, 581

Steidel, C. C. et al., 1996, ApJ, 462, L17

Webster, R. L. et al., 1995, Nature, 375, 469