NOAO Observing Proposal *CNTAC proposal* **Panel:** *For office use.*
Date: March 31, 2003 **Category:** High Z Galaxies

A Wide, Deep Near-IR Survey for Galaxies at $1 < z < 4$

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
As galaxy evolution began at very early epochs, understanding it requires observing to high redshift with techniques sensitive to different stellar populations. Hundreds of star-forming $z>2.5$ galaxies have been identified via the Lyman-break signature of inter-galactic hydrogen absorption in their rest-frame UV spectra. However, our $\Lambda\simeq0.7$ universe is $\sim$3 Gyr old at $z=2.5$, so galaxies which formed most of their stars at $z>2.5$, or are significantly dusty, can be sufficiently red or UV-faint to be missed by this technique. Such passively evolving galaxies remain difficult to select at all $z>1$ in *observed-frame optical* surveys – biasing our census of the high redshift galaxy population. We are reducing this bias with a *rest-frame optical* survey for galaxies at $1<z<4$, where the Balmer and 4000 Å break features of moderately old stellar populations produce a strong signal in the observed $R-J/J-K$ colors. By selecting galaxies more by stellar mass than by current star formation, we probe the oldest high-z galaxies, for the strongest constraints on structure formation models. We will identify $\sim$1500 $1<z<4$ galaxies and constrain their space density, spatial clustering and star formation history with a two-pronged survey using time from both CNTAC and NOAO: a wide component of $\sim$1 deg^2 ISPI imaging to J=22.65 (3σ) and K_s=20.5 (5σ) in fields with existing deep optical data, and a 1 mag deeper JHK_s survey over 0.1 deg^2 to probe farther down the luminosity function. The wide-survey data will be available immediately to the entire Chilean community.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	ISPI	6	bright	Nov - Dec	Aug - Jan
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines).*

This project **does not** require a contiguous time allocation, as most of the project members are located in Chile.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

Systematic optical surveys have generated an impressive census of the field galaxy population at redshifts $z<1$ (Crampton et al. 1995; Yee et al. 2000) and at redshifts $z>2.5$ (Steidel et al. 1996). Such surveys show that considerable star formation in massive galaxies, both in clusters and in the field, occurred at $z>1$ (see review by Peebles 2002). In fact, in early-type cluster galaxies, half the star formation is estimated to have occurred at $z>2$ (van Dokkum & Franx 2001). However, the range of stellar populations actually present in galaxies at redshifts $z>1$ remains poorly constrained. At such redshifts, optical surveys fail to isolate the photometric signature of target galaxies from lower redshift contaminants, and most NIR studies (e.g. da Costa et al. 1998) have been restricted by limited detector field of view. Hundreds of $z>2.5$ galaxies have been found with the 'Lyman-break' technique (Steidel et al. 1999), but this method requires a UV-bright, relatively flat-in-f_ν source, and thus is only sensitive to star-forming galaxies. Galaxies that formed the majority of their stars at redshifts $z\gg2.5$ and evolved passively since that epoch, and those containing a significant dust component ($E(B-V)\gtrsim0.4$ with the Calzetti (1997) extinction curve), will be systematically under-represented in Lyman break surveys.

To reduce this bias, we have begun a rest-frame optically selected survey of stellar populations in $\gtrsim0.5L^*$ galaxies at $1<z<4$, using ISPI. This survey is directly comparable to $z<1$ optical surveys. It selects galaxies more by their stellar masses than by their current star formation, due to its sensitivity to old stellar populations (though it is also sensitive to moderately dusty star formation). At $1<z<4$ the redshifting of the 4000Å and Balmer breaks through the J band produces a strong photometric signal in the RJK_s color plane (Fig. 2). A small amount of star formation can bluen such galaxies in $R-J$, but their mature stellar populations will keep them red in $J-K_s$, and they will still be selected in our survey. Optically faint galaxies with a range of optical colors but with red $J-K_s$ indicative of dominantly old (or dusty) populations at $z\gtrsim2$ have been identified and spectroscopically confirmed in small-area searches (van Dokkum et al. 2003, Franx et al. 2003, Dickinson et al. 2000, Totani et al. 2001) and along AGN sightlines (Francis et al. 1996, Hall et al. 2001). It is now clear that luminous, mature-population-dominated galaxies *do* exist at $z\gtrsim1.5$, but only a survey such as ours, with both wide (1 deg^2, $K_s\leq20.5$) and deep ($K_s\leq21.5$, 0.1 deg^2) components, can accurately determine their space density and luminosity function given the strong surface density variations in smaller surveys (Daddi et al. 2003, Eisenhardt et al. 2000). The deep component distinguishes us from the H-band LCIRS (McCarthy et al. 2001, currently being extended to JHK), while our comparable wide surveys enable studies of cosmic variance (Fig. 1).

The $\sim$1500 galaxies at $1<z<4$ which we expect to find, selected by mature stellar populations, will test two key components of galaxy formation models: the redshift interval over which massive galaxies assembled, and whether they did so in isolation or via the merging of sub-galactic units (Kauffmann 1996; Baugh et al. 1996). The optical/NIR colors of distant galaxies constrain the star formation history and total stellar mass of the luminosity weighted stellar populations (Barger et al. 1999, Shapley et al. 2001). The angular correlation of $1<z<4$ galaxies tests the hierarchical prediction that mature high-z stellar populations should be strongly clustered. Accurately measuring the space density of $\sim L^*$ galaxies at $1<z<4$ will provide a critical link to $z<1$ galaxy populations and reveal how representative Lyman break galaxies are of the high-z $\sim L^*$ galaxy population.

By overlapping with existing and planned deep multiwavelength surveys we also expect to find $\gtrsim$200 AGN via reddening-insensitive X-ray and optical-NIR color criteria (Warren et al. 2000, Barkhouse & Hall 2001). Also, our combined deep optical-NIR images will yield $>10^4$ faint galaxy photometric redshifts, which are especially needed in fields with X-ray data, as the redshift distribution of faint X-ray sources does not match current model predictions (Franceschini et al., astro-ph/0205529).

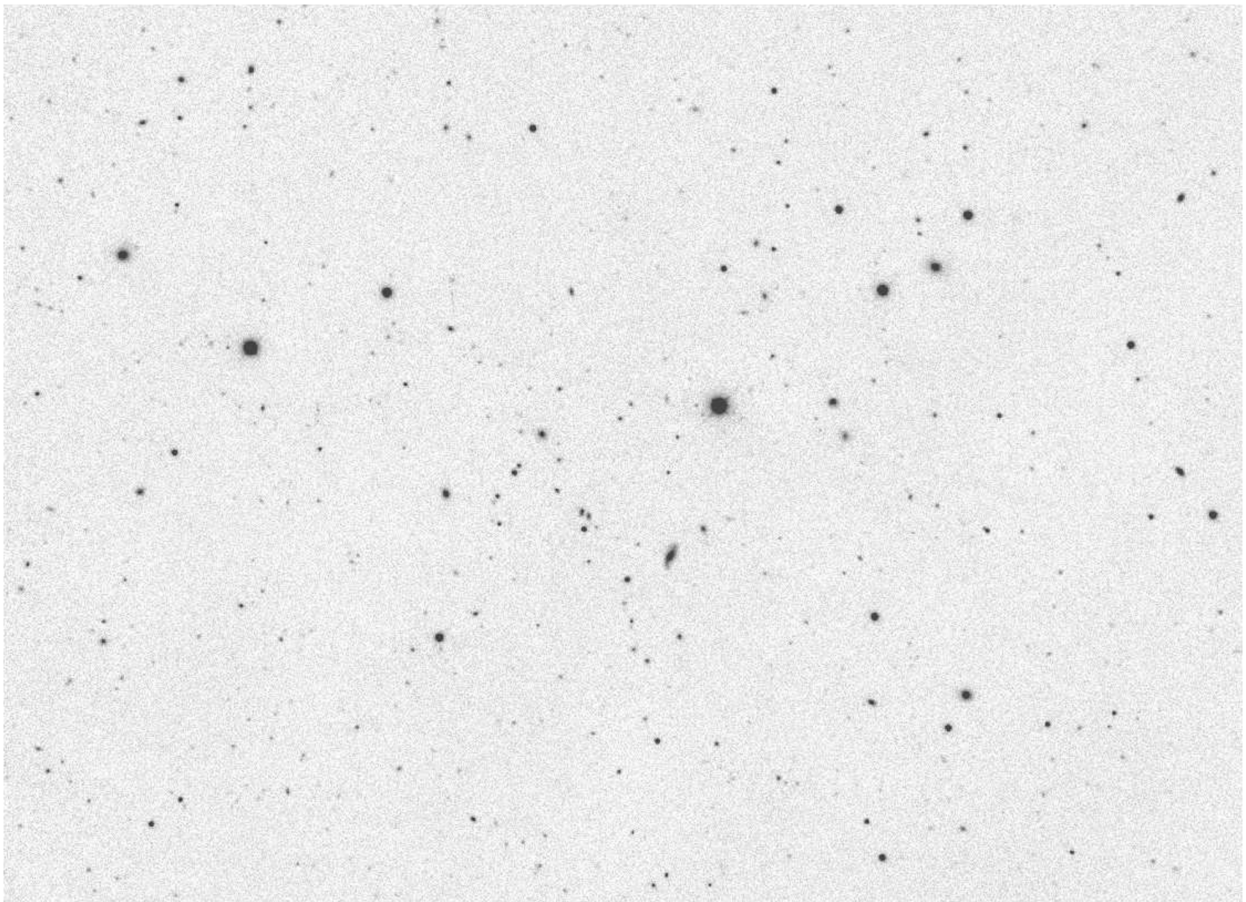

Figure 1: 9′ wide image showing about 2/3 of one wide-survey K_s-band ISPI pointing, in the field of the $z = 6.28$ quasar SDSS J1030+0524, which will soon have a ∼100 ksec XMM pointing. The clearly visible cluster probably amplifies the quasar's flux by a factor ∼2.

References

Barger et al. 1999 AJ 117 102
Baugh et al. 1996 MNRAS 283 1361
Crampton et al. 1995 ApJ 455 96
Dickinson et al. 2000 ApJ 531 624
Francis et al. 1996 ApJ 457 490
Gladders & Yee 2001 ASP Conf. Ser. 232 p. 126
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Shapley et al. 2001 ApJ 562 95
Steidel et al. 1999 ApJ 519 1
Totani et al. 2001 ApJL 558 L87
Warren et al. 2000 MNRAS 312 827
van Dokkum et al. 2003 Apr. 20, ApJL vol. 587
Barkhouse & Hall 2001 AJ 121 2843
Calzetti, D., 1997 AJ 113 162
da Costa et al. 1998 astro-ph/9812105
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Franx et al. 2003 Apr. 20, ApJL vol. 587
Hall et al. 2001 AJ 121 1840
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Peebles, P. J. E. 2002 astro-ph/0201015
Rudnick et al. 2001 AJ 122 2205
Steidel et al. 1996 ApJ 462 17
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Waddington, I., 1998, astro-ph/9801149
van Dokkum & Franx 2001 ApJ 553 90
Yee et al. 2000 ApJS 129 475

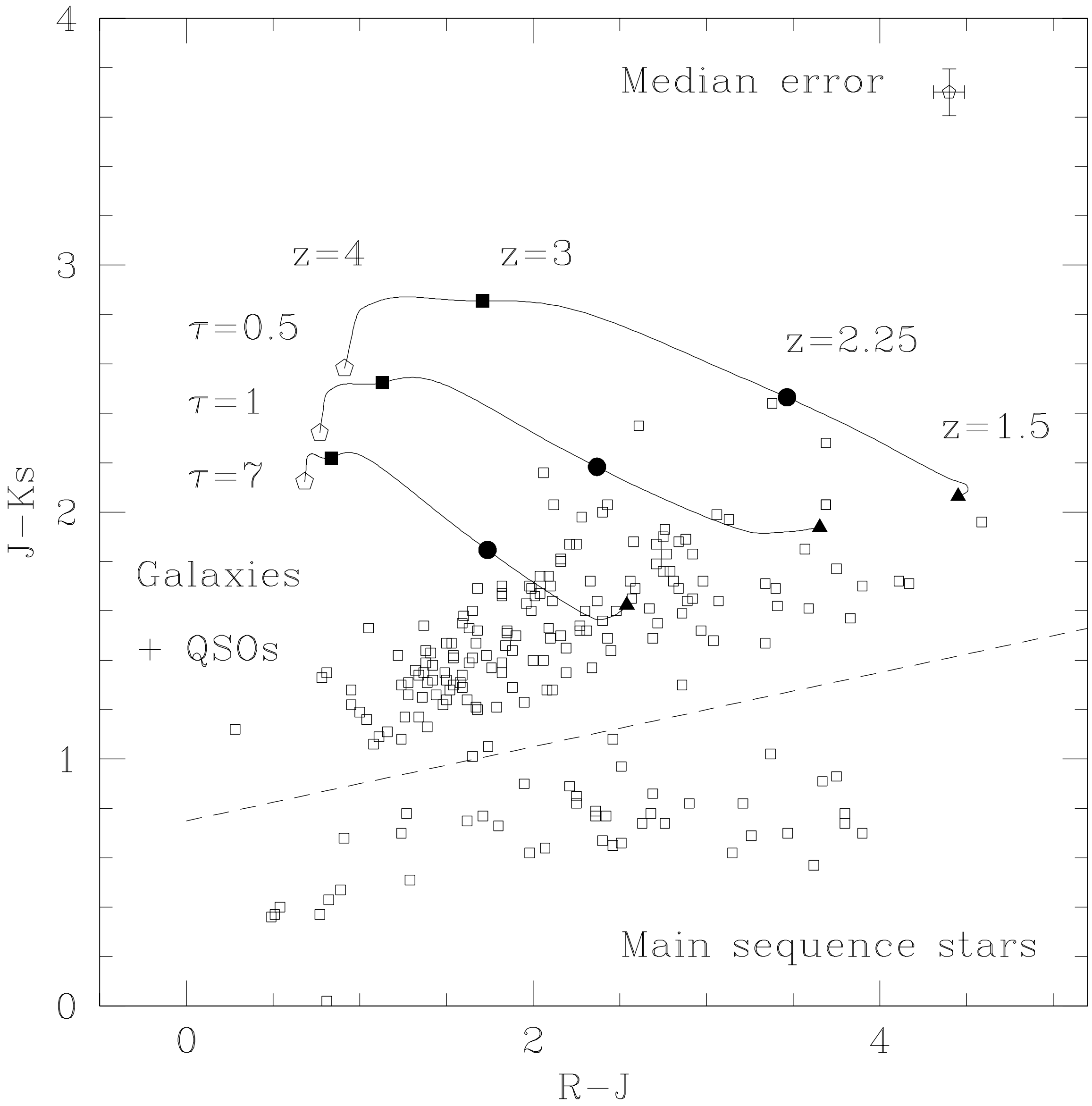

Figure 2: RJK_s diagram of 208 objects with K_s<21 from the 23 arcmin^2 deep NTT SUSI/SOFI field centred on HDF-South. This field represents $\sim 0.5\%$ of our wide-survey area and is observed to roughly the same depth. The galaxy distribution is clearly evident and well separated from the stellar main sequence. The three loci indicate the location of a solar metallicity galaxy population formed at redshift $z_f = 10$ in an exponentially declining burst of star formation if e–folding timescale 0.5, 1 and 7 Gyr respectively. The points on the loci trace the positions of these galaxies on the RJK_s plane as observed at redshifts 1.5, 2.25, 3 and 4 respectively. Low redshift ($z < 1$) galaxies populate the region blueward of $R - J < 2$ and $J - K_s < 1.5$. Applying the threshold $J - K_s > 1.9$ (Eisenhardt et al. 2000) to identify galaxies at redshifts $z > 1$ isolates 17 galaxy candidates in this field, corresponding to $\sim$1200 $z > 1$ galaxies in the total wide-survey area. The deep survey will detect $\gtrsim$300 fainter $z > 1$ galaxies, and will reach $z \simeq 4$ rather than $z \simeq 3$.

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

NIR observations are needed for our desired rest-frame census of galaxies at $1<z<4$. Our approach is a two-pronged one: a wide (1 deg^2) survey to find the rare, brightest examples of galaxies to $z\simeq3$, and a $\sim$1 mag deeper survey over 0.1 deg^2 to sample the larger population of fainter galaxies, and to reach $z\simeq4$. The wide survey component consists of 4 $0\overset{\circ}{.}5\times0\overset{\circ}{.}5$ fields (9 ISPI pointings each) to K_s=20.5 (5σ) and J=22.65 (3σ) and we aim for 85% completion by the end of 2004A. The deep survey component consists of a $\sim$1 mag deeper JHK_s survey of $0\overset{\circ}{.}17\times0\overset{\circ}{.}17$ fields (1 ISPI pointing each) located within the wide survey fields, observed at a rate of 1 ISPI pointing per semester. Many objects in the deep survey will be too faint for spectroscopy for the foreseeable future, and so the H band offers the only real way to improve the photometric redshifts and stellar population modelling of the $z>2$ mature galaxy population in the deep survey. Spectroscopy will be possible for many wide-survey objects (van Dokkum et al. 2003), however, and as ISPI has lower QE than expected, we have dropped our planned wide-field H imaging. Note that *all* 2048^2 IR arrays suffer this problem, as Rockwell is the sole supplier of such arrays, so ISPI still has a competitive advantage for the wide-field NIR surveys needed for a fair census of high-z galaxies. We also have a head start – our survey was the only high-z survey with ISPI in 2002B and 2003A.

Our target fields are near the HDF-South and CDF-South, plus two optimal equatorial fields for the A semester. The first is centered on the z=6.28 quasar SDSS J1030+0524; it is scheduled for a $\sim$100 ksec XMM pointing, we have obtained IJK data on this field in early 2003, and a smaller, deeper IzJ pointing has been obtained in this field with VLT. The second field, at J125540+010700, was selected after an exhaustive inspection of 100μm dust maps and POSS plates, to find a low-extinction hole with no stars brighter than m=11 in the MOSAIC field; we will obtain our first MOSAIC and ISPI data in this field in May 2003. Our other fields have optical imaging to at least $R\simeq25$ or $I\simeq24$ (required for the wide survey), and typically much more (see the target table). Furthermore, the CDF-S will be surveyed deeply with SIRTF; the HDF-S has been imaged in the optical, radio, and mid-IR; and, as mentioned, the SDSS field will have a $\sim$100 ksec XMM pointing.

As discussed above, J and K_s will be used for the wide survey. When combined with existing R or I data they enable selection of galaxies at $1<z<3$ (wide) and $1<z<4$ (deep), as discussed below. With H-band imaging also available for the deep survey, the combination of e.g. $R-J$, $J-H$ and $H-K_s$ will enable clearer identification of dust-enshrouded galaxies and better separation of galaxies dominated by mature stellar populations at $z\gtrsim1$ into $1\lesssim z\lesssim2$ and $2\lesssim z\lesssim3$ redshift bins (Waddington 1998). Additional optical filters will reduce $z<1$ galaxy contamination in the $z>1$ sample and will add to the deep survey by providing photometric redshifts for blue $z>1$ galaxies.

Eisenhardt et al. (2000) argue that the criteria $J-K_s>1.9$, $K_s<21$ efficiently identifies galaxies at $z\gtrsim1$. We have tested this prediction with the Rudnick et al. (2001) NIR photometric redshift catalogue of the HDFS: of the 13 objects with $J-K_s>1.9$ and $K_s<21$, 11 have $z_{phot}>1$ and 6 $z_{phot}>1.5$. Applying these results to the wider area catalogue of da Costa et al. (1998), which provides optical-NIR photometry of 23 arcmin^2 around the HDFS (Fig. 2), we find 17 objects with $J-K_s>1.9$ and $K_s<21$, of which 14 are expected to lie at $z>1$. Scaling to the area and depth of our wide ISPI survey, we expect to identify $\sim$1200$\pm$300 mature-population-dominated galaxies at $z>1$ (plus $\sim$300 more in the deep survey), of which $\sim$600$\pm$150 should be at $z>2$. The huge uncertainty in the expected number of galaxies is due solely to the small area covered by current surveys – we will constrain the surface density of $z>1$ NIR selected galaxies within 4% and will provide a direct test of the hierarchical model of galaxy formation (Kauffmann & Charlot 1998).

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

To maximize the scientific return from this survey, we will target fields which have pre-existing optical data (extremely useful for constraining the SEDs of near-IR selected galaxies) and which either have existing multiwavelength followup, or are well suited for future multiwavelength studies.

Thus we are targeting fields around the Chandra Deep Field South (Chandra, XMM, HST, SIRTF, plus optical imaging from ESO) and the Hubble Deep Field South (HST, ATCA, ISO, optical data from CTIO, proposed Chandra and XMM) plus two optimal equatorial fields for the A semester: SDSS J1030+0524 ($\sim$100 ksec XMM, wide-field optical data from CTIO and a smaller, deeper IzJ pointing from VLT) and 'Castander's Window' at J125540+010700, which is the only low-extinction region for many degrees around, and is thus well-suited for future multiwavelength followup.

We believe our wide+deep survey design, in carefully chosen fields, best serves the scientific interests of the community. Because of the strong interest in and commitment to the wide+deep approach at Calan, Catolica, and Yale, this is truly a joint effort of these institutions. In the spirit of collaboration encouraged by the FONDAP program between U. Chile, Catolica and Concepcion, we intend the wide survey to be a resource for the Chilean astronomy community, especially students and postdocs. Reduction of near-IR imaging data is straightforward, and we will make the coadded wide-survey images available to the Chilean community (and our collaborators at Yale) as soon as we produce them. Constructing optical/near-IR catalogs will take longer, but we will also make those wide-survey data products available as soon as they are produced.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

$\boxed{\star}$ **Maza, Hall, Gawiser, Willis, Treister, Barrientos, Infante, van Dokkum, Urry, Minniti, Castander, Coppi**: 6 CNTAC ISPI nights in May 2003 to begin combined wide+deep survey

$\boxed{\star}$ **Hall, Willis, Treister, Castander, Barrientos, Infante, Minniti**: 4 CNTAC ISPI nights 2002B to begin wide survey; 3 ISPI pointings completed in JK_s and one in K_s in $\sim$3 good nights. Initial characterization of the instrument and production of coadded images is underway

$\boxed{\star}$ **Gawiser, Maza, Castander, Treister, Coppi, Urry**: MOSAICII multicolor deep optical imaging of deep survey fields: 4 CNTAC nights in 2002B, run successful, preliminary reductions complete, awaiting more data in 2003 to complete fields; 3 CNTAC nights upcoming in May 2003

Observing Run Details for Run 1: CT-4m/ISPI

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

The CTIO4m+ISPI ($10.'25 \times 10.'25$ field of view) is the most efficient southern IR imaging survey instrument. The AAT4m+IRIS2 ($7.'7 \times 7.'7$ field) is at a site with worse seeing than CTIO. The NTT3.6m+SOFI has only a $5' \times 5'$ field of view. The LCO2.5m+CIRSI requires 4 pointings for a contiguous $13' \times 13'$ field. For ISPI, exposure times of 60 minutes in K_s and 160 in J reach limits of K=20.5 (5σ) and J=22.65 (3σ) for the wide survey. Overhead and calibrations should sum to 30% of the total exposure time; therefore, we require 4.75 hours per ISPI pointing. The deep survey will expose for 8 hours in K_s and 10 hours in J & H, reaching $\sim$1 mag deeper than the wide survey.

In the useful parts of the 4 ISPI nights awarded to begin a wide survey in Jan. 2003, we completed 1.5 ISPI pointings in the CDF-S (one pointing has only K_s data) and 2 in the SDSS field. (We expect overheads to be reduced from their rather high values in that run, and anticipate much lower overheads in upcoming ISPI runs.) In 2003A, we expect to obtain half the imaging required for the deep-survey pointings in the SDSS and HDF-S fields, plus 6 wide-survey pointings on the J1255 field (a large contiguous block of 6 ISPI pointings will be invaluable for a first good look at high-z galaxy clustering). In 2003B-2004A, our goals are to finish the deep pointings in the HDF-S and SDSS fields (4 nights total), observe a deep pointing in the CDF-S (4 nights), and complete the wide-field pointings in the HDF-S (8 pointings, 4 nights), the CDF-S (6.5 pointings, 3.5 nights), and the SDSS field (7 pointings, 3.5 nights). Therefore, this semester we are requesting 4 NOAO and 6 CNTAC nights, and in 2004A we expect to request 4 NOAO and 5 CNTAC nights. The survey will then consist of 3 deep pointings and 30 wide pointings (0.85 deg^2). This rapid timescale ensures that the surveys will have great scientific impact before the similarly deep but much larger multi-year UKIDSS survey begins sometime in 2004, using four 2048^2 IR arrays on the UKIRT-4m.

TARGET FIELDS

Name	RA (2000)	DEC (2000)	*l,b*	*E(B-V)*	Multiwavelength Data
HDFS-Flanking	22:32:56.0	−60:33:00.0	312,−46	0.028	*UBVRI*, ISO, ATCA
CDFS-Flanking	03:32:30.0	−27:48:30.0	233,−54	0.009	*UBVRI*, Chandra, SIRTF
SDSS z=6.28 QSO	10:30:30.0	+05:25:00.0	239,+50	0.024	Mosaic, ISPI, XMM
J1255+0107	12:55:40.0	+01:07:00.0	305,+64	0.015	upcoming Mosaic, ISPI

Instrument Configuration

Filters: JHK_s	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 03 to 22

Dec. range of principal targets (degrees): -60 to +05

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.7.