NOAO Observing Proposal *CNTAC proposal* **Panel:** *For office use.*
Date: October 1, 2002 **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)*:
Since 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, a Λ=0.7 universe is $\sim$3 Gyr old at z=2.5, and so galaxies which formed most of their stars at $z>2.5$, or are significantly dusty, would 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 will reduce 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 $\gtrsim$3000 $1<z<4$ 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 1.2 deg^2 ISPI imaging to $J\gtrsim23$, $H\gtrsim21.5$ and $K_s\gtrsim20.5$ (5σ) in fields with existing deep optical data, and a $\sim$1 mag deeper survey over 0.25 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	Apr - May	Feb - Jul
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 reviews by Ellis 2001 & 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 existing 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 (Fig. 1).

Thus we propose a rest-frame optically selected survey of stellar populations in $\gtrsim L^*+1$ galaxies at $1<z<4$, using ISPI. Such a survey is directly comparable to $z<1$ optical surveys and 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 and H bands 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 along AGN sightlines (Francis et al. 1996, Hall et al. 2001) and in small-area searches (Dickinson et al. 2000, Totani et al. 2001, van Dokkum in prep. 2002). It is also clear that luminous, mature-population-dominated galaxies *do* exist at $z\gtrsim1.5$ (Stockton 2001), but only a survey such as ours, with both wide (1.2 deg^2, $K_s\gtrsim20.5$) and deep ($K_s\simeq22$, 0.25 deg^2) components, can accurately determine their space density and luminosity function given the strong surface density variations in smaller surveys (Eisenhardt et al. 2000). The deep component distinguishes us from the LCIRS (McCarthy et al. 2001), while our comparable wide surveys enable studies of cosmic variance.

The $\gtrsim3000$ 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 $\gtrsim L^*$ 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 $\gtrsim L^*$ galaxy population.

By overlapping with existing and planned deep multiwavelength surveys (see Experimental Design), we also expect to find $\gtrsim200$ AGN via reddening-insensitive X-ray and optical-NIR color criteria (Warren et al. 2000, Barkhouse & Hall 2001), and, in the deep survey, near-IR variability. Also, our combined deep optical-NIR images will yield tens of thousands of faint galaxy photometric redshifts, which are especially needed in fields with X-ray data since the redshift distribution of faint X-ray sources does not match current model predictions (Franceschini et al. in press, astro-ph/0205529).

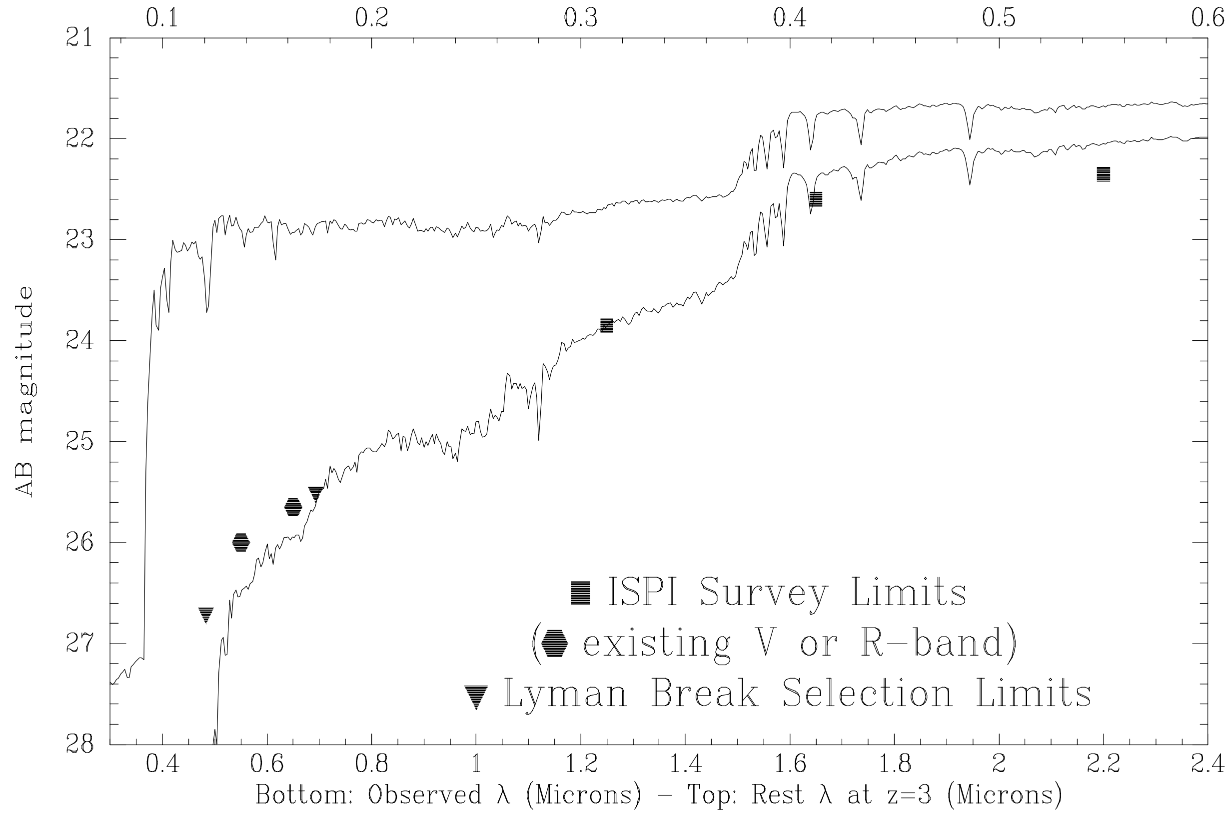

Figure 1: Comparison of Lyman-break and rest-frame-optical galaxy selection at z=3. The SEDs of two galaxies at z=3 are shown; the upper SED is that of a 1-Gyr-long burst at an age of 1 Gyr (i.e., constant star formation for 1 Gyr), and the lower SED is that of a 1-Gyr-long burst at an age of 1.2 Gyr. The triangles show the G and $\Re$ magnitude limits for the Lyman-break selection criteria of Shapley et al. (2001): only galaxies brighter in $\Re$ and bluer in $G{-}\Re$ than these limits are selected as Lyman-break galaxies (assuming they also have significant Lyα forest absorption in U). Only 0.2 Gyr after the end of star formation, a 1-Gyr-long burst no longer meets the Lyman-break selection criteria. The squares show our 3σ J and 5σ HK limits, and the hexagons the 5σ V or R limits of existing data. Both galaxies shown are detectable with our rest-frame optical selection criteria, which is much more sensitive to older stellar populations than to current star formation.

References

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Baugh et al. 1996 MNRAS 283 1361
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van Dokkum & Franx 2001 ApJ 553 90
Waddington, I., 1998, astro-ph/9801149
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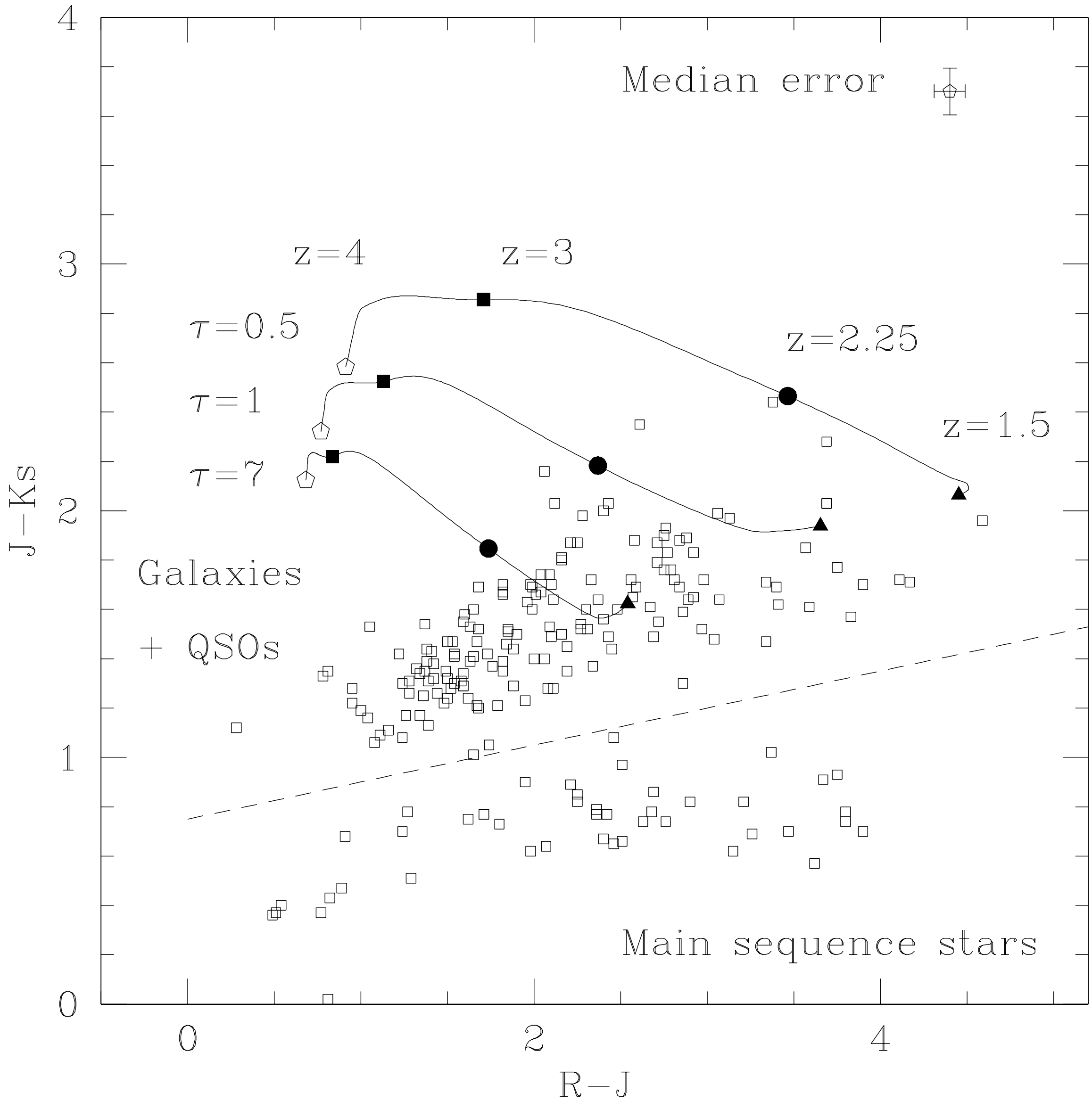

Figure 2: RJK_s diagram of 208 objects with K_s<21 from the 23 arcmin^2 deep NTT SUSI/SOFI field centred on HDF-South. This field represents $\sim 0.5\%$ of our wide-survey area and is observed to roughly the same depth. The galaxy distribution is clearly evident and well separated from the stellar main 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 2000-3000 $z > 1$ galaxies in the total wide-survey area. The deep survey will detect $\gtrsim$1000 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 (1.2 deg^2) survey to find the rare, brightest examples of galaxies to $z\simeq3$, and a $\sim$1 mag deeper survey over 0.25 deg^2 to sample the larger population of fainter galaxies, and to reach $z\simeq4$. The wide survey component consists of 4 $0.^{\circ}55\times0.^{\circ}55$ fields (9 ISPI pointings each) to $K_s\gtrsim20.5$, $H\gtrsim21.5$ and $J\gtrsim23$ (5σ) which will be 85% completed by the end of 2003. The deep survey component consists of of 4 $0.^{\circ}37\times0.^{\circ}18$ fields (2 ISPI pointings each) located within the wide survey fields, observed at a rate of 2 ISPI pointings per semester for four semesters. We believe our wide+deep survey design 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. Therefore we have been more broad and ambitious in our requests (to CNTAC *and* NOAO) than in last semester's CNTAC proposal.

Our main target fields are near the HDF-South and CDF-South, plus two A-semester fields to be finalized after time is assigned and we complete an exhaustive comparison of each candidate's relevant properties, e.g., N_H, $E(B-V)$, 100μm cirrus emission, bright star counts, quality of existing optical data, etc. All our fields have optical imaging to at least $V\simeq26$ or $R\simeq25$ (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 we plan to make our other two fields the basis for similar deep multiwavelength investigations.

J and K_s are the primary survey filters, since when combined with existing V or R data they enable selection of galaxies at $1<z<3$ (wide) and $1<z<4$ (deep), as discussed below. H-band imaging is also essential, however, since the combination of e.g. $R-J$, $J-H$ and $H-K_s$ will enable identification of dust-enshrouded galaxies, and separation of galaxies dominated by mature stellar populations at $z\gtrsim1$ into $1\lesssim z\lesssim2$ and $2\lesssim z\lesssim3$ bins in the wide survey (Waddington 1998). Additional optical filters will reduce $z<1$ galaxy contamination in the $z>1$ sample and will greatly add to the deep survey by providing photometric redshifts for blue $z>1$ galaxies, but for detecting old galaxies at high z such data are no substitute for H-band data around the redshifted 4000Å break.

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 of our wide ISPI survey (1.2 deg^2), we expect to identify $\sim$2700$\pm$650 mature-population-dominated galaxies at $z>1$, of which $\sim$1200$\pm$300 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 2% and will provide a direct test of the hierarchical model of galaxy formation (Kauffmann & Charlot 1998).

An important calibration of the above photometric redshift predictions will come from spectroscopic redshift catalogs of $1<z<4$ NIR-selected galaxies. Three members of the proposing team (Willis, Hall, Barrientos) are members of the Gemini South Flamingos demo science program, and will perform a NIR spectroscopic survey of $\sim$30 $H<22$ galaxies from the HDFS in November 2002. A fourth member (van Dokkum) has already obtained over a dozen optical redshifts of $1<z_{photo}<4$ NIR-selected galaxies, with an 80% success rate (van Dokkum et al. in prep., 2002).

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 will target fields near the Chandra Deep Field South (Chandra, HST, SIRTF, plus optical imaging from ESO) and the Hubble Deep Field South (HST, ATCA, ISO, optical data from CTIO) – though not overlapping existing deep optical/NIR pointings on the CDFS and HDFS proper – plus a Calan-Yale survey field (existing $J{\sim}22$ and $K{\sim}20$ data over $13' \times 13'$ fields from the LCO 2.5m, existing VI data from CTIO 4m + MOSAICII) and a Red-sequence Cluster Survey field (existing Rz data from CTIO 4m + MOSAICII). The latter two fields remain tentative, pending an exhaustive comparison of the various candidate fields listed in the target table.

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.*

$\boxed{\star}$ **Hall, Willis, Treister, Castander, Barrientos, Infante, Minniti**: 4 CNTAC ISPI nights 2002B (01/2003) for 1 deg^2 $K{\lesssim}21$ rest-frame optical survey of $1{<}z{<}3$ galaxies [begins wide survey]
$\boxed{\star}$ **Castander, Maza, Treister, Coppi, Gawiser**: 4 CNTAC MOSAICII nights 2002B (10/2002) for multicolor deep optical imaging of deep survey fields
• **Castander, Maza, Treister**, Guzmán, Zepf, **Coppi**: 1 CNTAC MOSAICII night in 2002A for deep UB imaging in Calan-Yale fields. Part of these data used in Castander et al. 2002, submitted.
• **Hall**: CTIO1.5m: 12 CNTAC nights 2001AB for 2MASS-selected AGN candidate spectroscopy; selection 65% efficient; paper on serendipitous flaring L dwarf published; AGN paper submitted
• **Hall**, **Barrientos**, Gladders, Yee, De Robertis: CTIO4m+OSIRIS 2 CNTAC nights 2001A, and KPNO4m+SQIID 4 nights 2002B, for near-IR imaging followup of candidate brown dwarfs & $z{>}5.5$ quasars from Red-Sequence Cluster Survey; deeper IR followup of 5 potential quasar candidates has ruled them out; many L and T dwarf candidates found, including a candidate L4-L5 10,000-AU binary; 3 good nights of SQIID data being reduced; program continuing at CFHT and Magellan
• **Barrientos**, Yee, Gladders, Ellingson, **Hall**, **Infante**, Kodama: CTIO4m+MOSAIC: 16 CNTAC+NOAO nights 1999B - 2001B for southern Red-Sequence Cluster Survey imaging; 45 deg^2 imaged; first results paper about to be submitted; first catalog paper in preparation

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).*

ISPI on the CTIO-4m ($11'\times11'$ field of view) is simply the most efficient IR imaging survey instrument in the southern hemisphere. SOFI on the NTT-3.6m has only a $5'\times5'$ field of view. CIRSI on the LCO-2.5m requires 4 pointings to achieve a single contiguous $13'\times13'$ field of view. For ISPI, we estimate exposure times of 60 minutes each in K_s and H and 100 in J to reach magnitude limits of K=20.5 and H=21.5 (5σ) and J=23 (3σ) for the wide survey. **We believe these estimates to be pessimistic** based on our experience at the KPNO-4m and the LCO-2.5m. Nonetheless, we have used these numbers for fair comparison to other proposals. If these numbers are correct, we can reach our science goals in the requested time, but if they are indeed pessimistic, we will maintain the quoted exposure times. The increased depth will yield a great return in the number of $1<z<3$ galaxies, since we are probing the steep end of the luminosity function at L^* and above. We thus require 4.5 hours per ISPI pointing (20% of that being overhead and calibrations). The deep survey will expose for 6 hours in each band, reaching $\sim$0.85 mags deeper than the wide survey.

Our four target fields are the HDF-S and CDF-S 'flanking' fields and two A-semester fields, tentatively a Calan-Yale survey field at 1130-15 and a Red-sequence Cluster Survey field on the equator at 13 or 14 hours RA. We have several backup fields to ensure flexibility depending on when time is assigned; see the Experimental Design section for full details. In our 4 ISPI nights awarded to begin a wide survey in Jan. 2003, we will observe the CDF-S [3 wide-survey ISPI pointings] and the Calan-Yale and RCS fields [2 wide-survey pointings each]. In 2003A, five nights in April or May are required to finish the wide survey of the RCS field [7 ISPI pointings]; one complete field will be invaluable for a first look at high-z galaxy clustering, and 7 other pointings can be placed on the HDFS and Calan-Yale field during the same run. Five nights are also required for the deep survey to complete two deep pointings, one each in the Calan-Yale and RCS fields. To obtain the required total of ten nights, we are requesting 6 CNTAC and 4 NOAO nights in 2003A, and will split the total time granted in half between the two surveys. Thus, from 1 to 3 nights of a 6-night CNTAC award would be spent on the deep survey, and the rest on the wide survey. We expect to request 5 CNTAC + 3 NOAO nights in 2003B, making the wide survey 85% complete and the deep survey 50% complete by the end of 2003. This rapid timescale ensures that the surveys will have great scientific impact before the similarly deep but much larger multi-year UKIDSS survey begins in 2004, using four 2k x 2k IR arrays on the UKIRT 4m.

TARGET FIELDS

Name	RA (2000)	DEC (2000)	l,b	$E(B$-$V)$	Priority; Multiwavelength Data
MS1054-03	10:54:00.0	−03:00:00.0	256,+49	0.041	C? (backup); HST-ACS, Chandra, VLA
ESO-DPS	11:21:27.0	−21:42:30.0	277,+37	0.048	B? (backup); $UBVRI$
Calan-YaleC5	11:30:00.0	−14:49:00.0	276,+44	0.036	A?; $VRIJK$, some U, Chandra
Calan-YaleC2	12:53:00.0	−09:24:00.0	305,+53	0.044	C? (backup); $VIJK$, some UB, Chandra
RCSS-1950	13:17:00.0	−03:00:00.0	217,+59	0.036	B? (backup); Rz
RCSS-1950	14:34:00.0	−01:00:00.0	349,+52	0.039	A?; Rz
HDFS-Flanking	22:32:56.0	−60:33:00.0	312,−46	0.028	(A); $UBVRI$, ISO, ATCA
CDFS-Flanking	03:33:00.0	−27:30:00.0	233,−54	0.009	(A); $UBVRI$, Chandra, SIRTF

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): 11 to 23

Dec. range of principal targets (degrees): -01 to -60

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