**NOAO Observing Proposal** *CNTAC proposal* **Panel:** *For office use.*
*Date:* April 1, 2002 **Category:** High Z Galaxies

# A Rest-Frame Optical Survey for Galaxies at $1 < z < 3$


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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 multiwavelength techniques sensitive to different galaxy components. Hundreds of $z{>}2.5$ galaxies have been identified via the 'Lyman-break' signature of inter-galactic hydrogen absorption in the spectra of star-forming galaxies with high rest-frame UV fluxes. However, a $\Lambda$=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, could be sufficiently red or UV-faint to be missed by this technique. Such passively evolving galaxies can remain difficult to select at all $z{>}1$ in *observed*-frame optical surveys – biasing our census of the high redshift galaxy population. We propose to reduce this bias with a *rest*-frame optical survey for galaxies at redshifts $1{<}z{<}3$, where the Balmer and 4000 Å break features of moderately old stellar populations produce a strong signal in the observed $J-K$ color. By selecting galaxies more by stellar mass than by current star formation, we probe the oldest, most massive high-$z$ galaxies, for the strongest constraints on structure formation models. The survey should identify $\sim$1500 $1{<}z{<}3$ galaxies and constrain their space density, spatial clustering and star formation history. The survey requires ISPI imaging of 1 deg$^2$ to $J{\gtrsim}23$ ($3\sigma$), $H{\gtrsim}21.25$ and $K_s{\gtrsim}20.5$ ($5\sigma$), in fields with existing deep optical and moderately deep near-IR data, over three semesters. Data and catalogs will be made 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 | 4 | bright | Sep - 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. The location of most of the project members in Chile ensures that we can respond positively to flexible scheduling arrangements.

**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 in the key redshift interval $1<z<3$ remains poorly constrained. At such redshifts, optical surveys fail to isolate the photometric signature of target galaxies from lower redshift contaminants, and most 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-$f_\nu$ 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 displaying 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 $\gtrsim L^*$ galaxies at $1<z<3$, using the CTIO4m+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 $1<z<3$ the redshifting of the 4000Å and Balmer break features 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 in small-area searches (Dickinson et al. 2000, Totani et al. 2001), and along AGN sightlines (Francis et al. 1996, Hall et al. 2001). It is also clear that luminous mature-population-dominated galaxies exist at $z\gtrsim1.5$ (Stockton 2001), but only a deep ($K_s\gtrsim20.5$), wide-field (1 deg$^2$) survey such as ours can accurately determine their space density, given the strong variation seen in their surface density in smaller surveys (Eisenhardt et al. 2000). We reach $\sim0.^{\rm m}5$ deeper than the LCIRS (McCarthy et al. 2001) over a similar area, valuable since we still probe only the bright end of the LF at $z>1$.

The $\sim$1500 galaxies at redshifts $1<z<3$ in our survey, selected by their mature stellar populations, will test two key components of galaxy formation models: the redshift interval over which massive galaxies assembled, and whether they assembled in isolation or via the merging of sub-galactic units (Kauffmann 1996; Baugh et al. 1996). Our accurate measurement of the space density of $L^*$ galaxies at $1<z<3$ will also provide an important link to galaxy populations at $z<1$ and address the issue of how representative Lyman break galaxies are of the entire $\gtrsim L^*$ galaxy population. The angular correlation of optically red galaxies at $1<z<3$ will provide an important test of hierarchical galaxy formation, which predicts that mature stellar populations at high $z$ should be strongly clustered. Also, the optical/NIR colors of distant galaxies constrain the stellar masses and star formation history of their luminosity weighted stellar populations (Barger et al. 1999, Shapley et al. 2001).

We will overlap with the 0.25 deg$^2$ $K<20$ Calan-Yale IR survey. Second-epoch data will increase our depth and enable proper motion and variability studies. We expect to detect $\sim$200 quasars using a combination of X-ray and near-IR variability and color selection (Warren et al. 2000, Barkhouse & Hall 2001). The combined quasar-galaxy sample will permit the first unbiased assessment of quasar-galaxy clustering at $1<z<3$. Another subproduct will be the first sample of low-redshift low surface brightness galaxies detected in the near-IR. We expect to reach $\mu_0(K_s)\sim20.3$ ($\mu_0(B)\sim22.8$).

**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 required for a representive census of galaxies at $1<z<3$. We propose to observe two $0.^\circ55\times0.^\circ55$ fields (9 ISPI pointings each) and two $0.^\circ37\times0.^\circ55$ fields (6 ISPI pointings) to $K_s$=20.5 and $H$=21.25 ($5\sigma$) and $J$=23 ($3\sigma$) over three semesters. Here we request **four nights observing time** to complete $\sim$1/3 of the survey. Our target fields surround the Calan-Yale IR survey fields, which have $K\sim20$ and $J\sim22$ data from LCO, enabling variability and proper motion studies (and increased depth) over $0.25\square^\circ$. Target & backup fields also have deep images in $V$ (Calan-Yale) or $R$ (Red-sequence Cluster Survey; Gladders & Yee 2001). $J$ and $K_s$ are the primary survey filters, since (combined with existing $V$ or $R$ data) they enable the selection of galaxies at $1<z<3$, as discussed below. $H$-band imaging is also important, however, since the combination of $V-J$ (or $R-J$), $J-H$ 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 (Waddington 1998). Additional, shallower optical data (e.g. $UBI$ in Calan-Yale fields and $z$ in RCS fields) will reduce $z<1$ galaxy contamination in the $z>1$ sample, and will improve photometric redshifts for some $z>1$ galaxies, but is not a 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 redshifts $z\gtrsim1$. We have tested this prediction with the Rudnick et al. (2001) NIR photometric redshift catalogue of the HDF-South, which provides $JHK_s$ magnitudes and optical-NIR photometric redshifts for 136 objects. Of the 13 objects with $J-K_s>1.9$ and $K_s<21$, 11 have $z_{phot}>1$ and 6 $z_{phot}>1.5$. For a better estimate of the surface density of such objects, we apply these results to the wider area catalogue of da Costa et al. (1998), which provides optical-NIR photometry of a 23 arcmin$^2$ area centred on the HDF-South. All objects in this catalogue with $K_s<21$ are plotted in Fig. 2. We find 17 objects satisfying $J-K_s>1.9$ and $K_s<21$, of which 14 are expected to lie at $z>1$. By scaling these values to the proposed area of our ISPI survey (1 deg$^2$) we anticipate the identification of 2000±500 galaxies satisfying $J-K_s>1.9$ and $K_s<21$, of which 1700±400 are expected to lie at $z>1$ and 800±200 at $z>2$. (Our nominal goal is $K_s$=20.5, in which case these numbers will be overestimates. However, we believe $K_s$=21 should be reachable with ISPI in the requested time, as discussed in the observing run details section.) The error in the expected number of galaxies is dominated by the small area covered by current surveys – our proposed ISPI survey 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).

Our numerous large fields enable robust measurement of the clustering properties $J-K_s>1.9$, $K_s<21$ galaxies, for a number of important scientific tests. Hierarchical galaxy formation predicts that the distribution of old galaxies at $z>1$ should trace regions of rapid, early galaxy assembly (Kauffmann 1996; Baugh et al. 1996); such an inhomogeneous distribution of galaxies will generate a strong clustering signal in the ISPI sample (not to mention the possibility of detecting significantly overdense 'protoclusters'). Our two or more epochs of near-IR data will enable variability selection of quasars along with color and X-ray selection; the $\sim$200 quasars from our fields will permit a measurement of the cross-correlation signal between uniformly selected $z>1$ galaxies and quasars.

Three members of the proposing team (Willis, Hall, Barrientos) are members of the Gemini South Flamingos I science demonstration program. This program will perform a NIR spectroscopic survey $\sim$200 $K_s<21$ galaxies from the HDF-South and Chandra Deep Field South. This redshift catalogue will provide an important calibration of the above photometric redshift predictions and will maximise the spectroscopic information available over the redshift range of our ISPI survey.

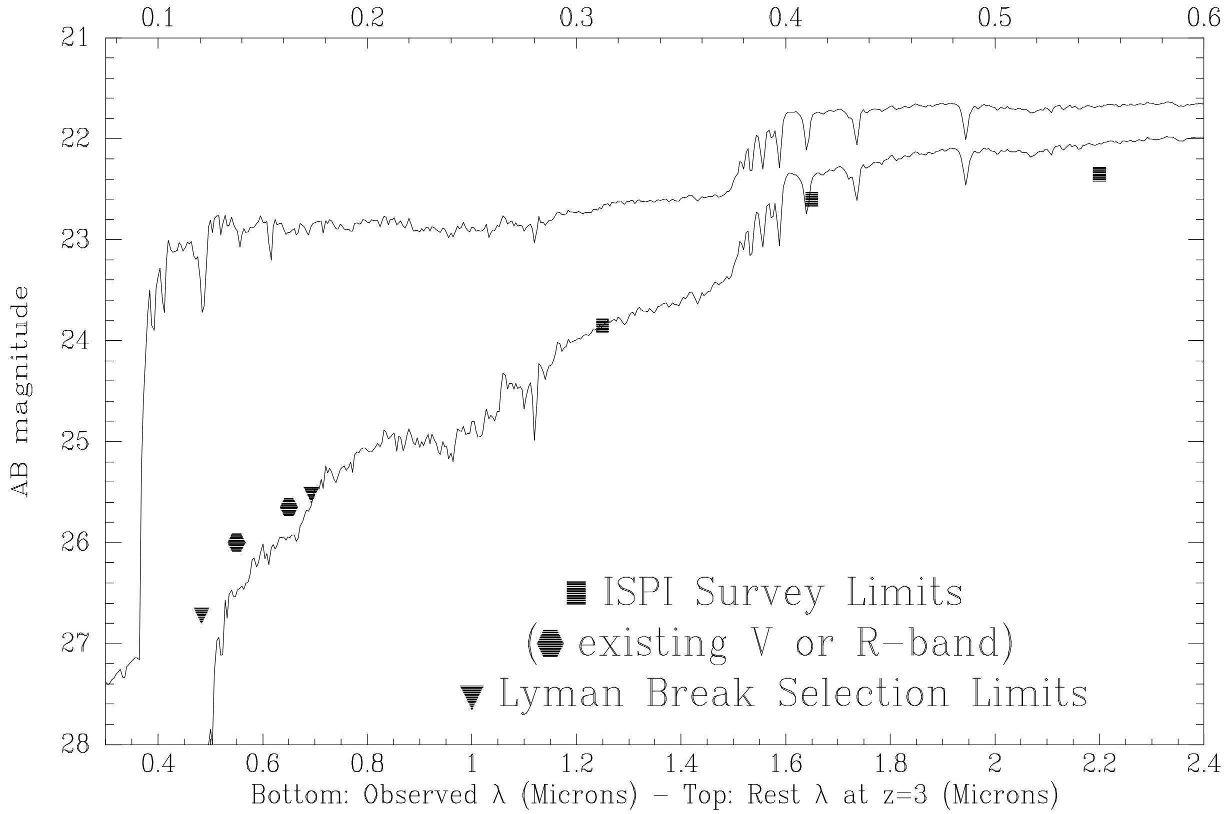


Figure 1: Comparison of Lyman-break and rest-frame-optical galaxy selection at $z$=3. The SEDs of two galaxies at $z$=3 are shown; the upper SED is that of a 1-Gyr-long burst at an age of 1 Gyr (i.e., constant star formation for 1 Gyr), and the lower SED is that of a 1-Gyr-long burst at an age of 1.2 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 Ly$\alpha$ 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 $3\sigma$ $J$ and $5\sigma$ $HK$ limits, and the hexagons the pre-existing $5\sigma$ $V$ or $R$ limits. 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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Crampton et al. 1995 ApJ 455 96
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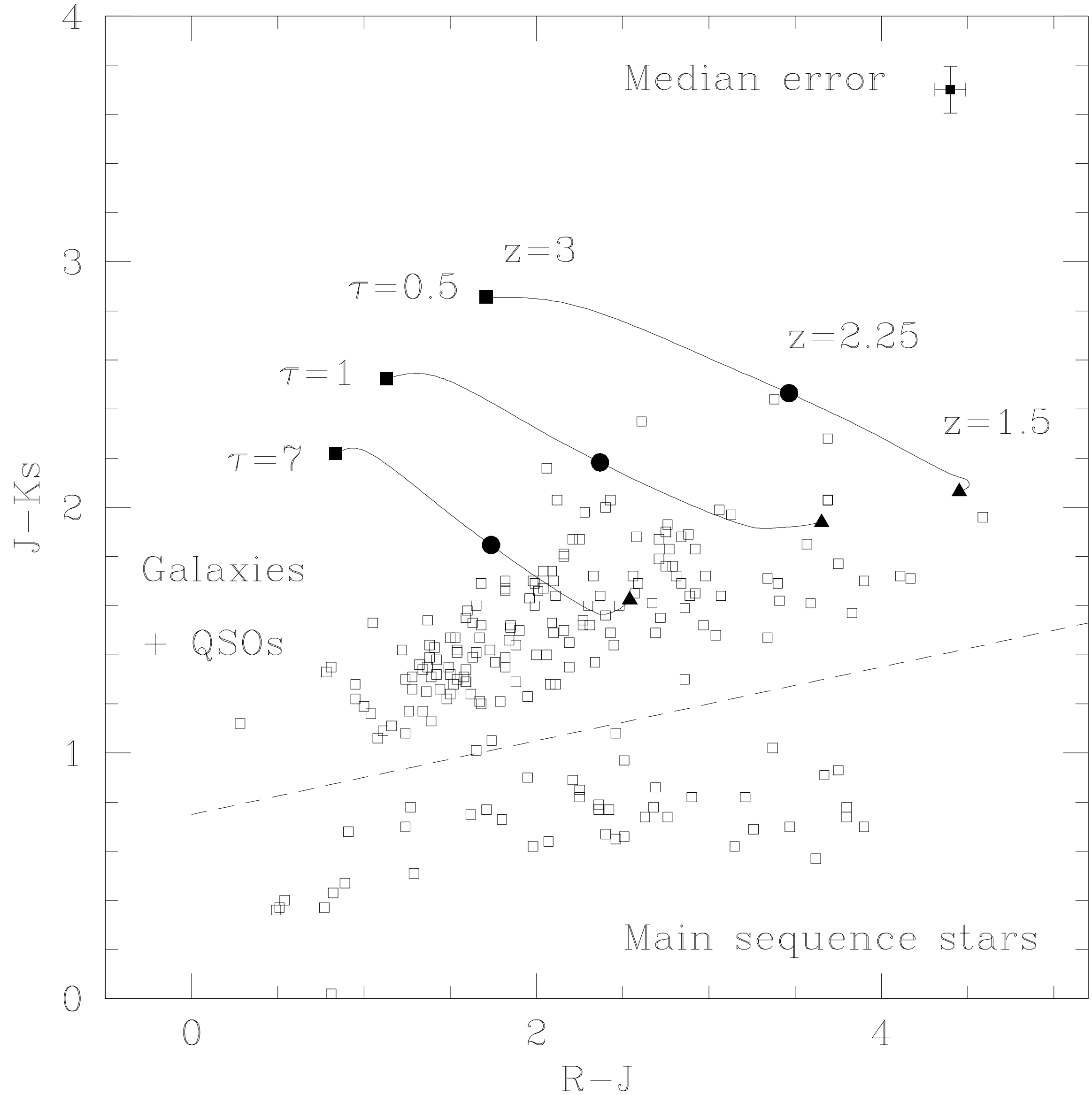


Figure 2: $RJK_s$ diagram of 208 objects with $K_s$<21 from the 23 arcmin$^2$ deep NTT SUSI/SOFI field centred on HDF-South. This field represents $\sim 1\%$ of our proposed survey area and is observed to the same depth (or slightly deeper). The galaxy distribution is clearly evident and well separated 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 loci trace the positions of these galaxies on the $RJK_s$ plane as observed at redshifts 1.5, 2.25 and 3 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 1500–2000 galaxies in the total survey area.

**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 from the Calan-Yale survey, which has existing $J$ and $K$ data (in $13'\times 13'$ fields) from the LCO 2.5m, existing $V$ and $I$ data ($36'\times 36'$) from the CTIO 4m, and deep ($\sim$50 ksec) public pointings from the *Chandra* X-ray observatory. The second-epoch near-IR data will enable us to create the first near-IR variability selected sample of AGN (as well as stars and possibly other transients), search for stars using proper motion, and of course increase the depth of the IR images available for one-fourth of the survey (0.25 deg$^2$), which will be helpful for identifying faint counterparts to X-ray sources. The pre-existing deep $V$ and shallower $I$ data will help constrain the SEDs of near-IR selected galaxies. Similarly, in our backup fields we have pre-existing deep $R$ and shallower $z$ data from the Red-sequence Cluster Survey conducted at the CTIO 4m. Some additional data ($UBz$) is available in some of the Calan-Yale area, and a separate proposal is being submitted for additional optical data, which if granted will leverage the value of our IR data (and vice versa).

In the spirit of collaboration encouraged by the FONDAP program between Catolica, U. Chile and Concepcion, we intend this survey to be a resource for the Chilean community (and for our collaborators at Yale). Reduction of near-IR imaging data is straightforward, and we will make the coadded images available to the above community as soon as we produce them. Production of near-IR and optical/near-IR catalogs will take a bit longer, but we will also make those 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.*

• **Hall**: CTIO1.5m+CSPEC: 6 nights each 2001A & 2001B for spectroscopy of 2MASS-selected AGN candidates; AGN selection criteria about 65% efficient; paper on serendipitous flaring L dwarf published; AGN paper in preparation
• **Hall**, Barrientos, Gladders, Yee, Sawicki, De Robertis: CTIO4m+OSIRIS: 2 nights 2001A for $J$ followup of candidate brown dwarfs & $z$>5.5 quasars from Red-Sequence Cluster Survey; 2 quasar and 6 T dwarf candidates found; followup underway
• **Hall**, Green, Kennefick, Osmer, Smith: 1 night Mar. 1999 w/CTIO4m+HYDRA for Big Faint Quasar Survey spectroscopy; 1 project & 1 backup Deep Multicolor Survey field observed; key targets missed due to instrument software errors; data reduced, results now in online DMS database
• Barrientos, Yee, Gladders, Ellingson, **Hall**, Infante, Kodama: CTIO4m+MOSAIC: 16 nights 1999B - 2001B for southern Red-Sequence Cluster Survey imaging; 45 deg$^2$ imaged; first results paper and first catalog paper in preparation
• Kennefick, Falco, Green, **Hall**, Osmer, Smith, Monier, Conti; 8 nights Fall 1999 - Fall 2000 for longslit spectra of candidate z>5 quasars & gravitational lenses from a 40 deg$^2$ BVIZ survey; two z$\sim$4.75 quasars found despite typically poor seeing & weather; paper about to be submitted

## 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 is quite simply the most efficient IR imaging survey instrument in the southern hemisphere. SOFI on the NTT-3.6m has only a $5' \times 5'$ field of view. CIRSI on the LCO-2.5m requires 4 pointings to achieve a single contiguous $13' \times 13'$ field of view.

Using the ISPI exposure time calculator, we estimate exposure times of 60 minutes each in $H$ and $K_s$, and 100 minutes in $J$, to reach our desired magnitude limits of $H$=21.25 and $K_s$=20.5 ($5\sigma$) and $J$=23 ($3\sigma$). **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 require 4.5 hours per ISPI pointing (20% of that being overhead and calibrations). Since we can work somewhat past astronomical twilight in the near-IR, we can observe slightly more than 2 ISPI pointings per bright-time night.

Our top target fields are the Calan-Yale IR survey fields. These fields have existing data to $J{\sim}22$, $K{\sim}20$ (in $13' \times 13'$ fields) and $V{\sim}26$, $I_{AB}{\sim}24$ ($36' \times 36'$). Our backup target fields are Red-sequence Cluster Survey fields with existing MOSAICII data to $R_{AB}{\sim}25.5$ and $z_{AB}{\sim}23$. For 2002B, we have two primary Calan-Yale fields (plus a backup where the optical data is not as deep), all with public *Chandra* pointings of ~50 ksec. In both fields we plan a 3x3 grid of ISPI pointings, overlapping the existing IR and optical imaging. This semester we request 4 nights, which is half the time required on these fields; we will request the remaining 4 nights in 2003B. We also plan to ask for 5 nights early in 2003A to place 3x2 grids of ISPI pointings on the remaining two Calan-Yale fields, one of which has two existing IR pointings.

**TARGET FIELDS**

| Name | RA (2000) | DEC (2000) | *l,b* | *E(B-V)* | Priority; Existing Data; Notes |
|---|---|---|---|---|---|
| Calan-YaleD1 | 22:01:00.0 | −31:46:00.0 | 16,−53 | 0.03 | B; $VIK$, $J$ scheduled; *Chandra* |
| Calan-YaleD2 | 23:48:00.0 | +00:57:00.0 | 92,−58 | 0.03 | C; $K$, some $UBIz$, $J$ scheduled; *Chandra* |
| Calan-YaleD3 | 03:38:00.0 | −05:03:00.0 | 192,−44 | 0.05 | A; $VIJK$, some $UB$; *Chandra* |
| RCSS-1950 | 05:16:00.0 | −43:00:00.0 | 248,−35 | 0.02 | D; $Rz$ |
| Calan-YaleC5 | 11:30:00.0 | −14:49:00.0 | 276,+44 | 0.04 | (B); $VIJK$, some $U$ |
| Calan-YaleC2 | 12:53:00.0 | −09:24:00.0 | 305,+53 | 0.05 | (A); $VIJK$, some $B$; 2 LCO fields |
| RCSS-1950 | 13:17:00.0 | −03:00:00.0 | 217,+59 | 0.03 | (C); $Rz$ |

**Instrument Configuration**

| | | |
|---|---|---|
| Filters: $JHK_s$ | Slit: | Fiber cable: |
| Grating/grism: | Multislit: | Corrector: |
| Order: | $\lambda_{\rm start}$: | Collimator: |
| Cross disperser: | $\lambda_{\rm end}$: | Atmos. disp. corr.: |

**R.A. range of principal targets (hours):** 22:01 to 03:38

**Dec. range of principal targets (degrees):** -32 to -05

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