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# SWIRE and SIRTF Surveys

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**Abstract.** The launch of SIRTF on August 25, 2003 opens an exciting new era for the infrared. Building on the legacy of IRAS, COBE & ISO, SIRTF will image the sky from 3.6−160 $\mu$m in tiered surveys, from wide (~80 sq. deg.) reaching z~1 in depth for $L^*_{FIR}$ galaxies, to small, deep, confusion-limited surveys. SIRTF will measure the accumulation of stellar mass at high redshift, and the evolution of dusty systems (disks, starbursts & AGN) since z~4, on size scales up to several hundred Mpc. The next decade will also see two major all-sky IR surveys, ASTRO-F and WISE (Wide-field Infrared Survey Explorer), and the launch of Herschel and Planck.

## 1. The Evolving Dusty Universe

A large fraction of the emission of stars and AGN in galaxies is absorbed and re-emitted by dust in the thermal infrared, as demonstrated dramatically by COBE detections of the Cosmic Infrared Background (CIB) (Puget et al. 1996; Hauser & Dwek 2001). Extremely high IR emission fractions (>90%) can occur in luminous starbursts and AGN, usually from the central 100−1000 pc unlike the more distributed UV-optical emission.

ISO surveyed extensively from 6.7 to 170 $\mu$m (Genzel & Cesarsky 2000; Franceschini et al. 2001; Rowan-Robinson et al. 2004), reaching a peak in the 15 $\mu$m number counts near 0.3 mJy which is dominated by Luminous Infrared Galaxies (LIRGs) at redshifts of ~0.8−1 (Elbaz et al. 2002). About 70−80% of the mid-IR CIB is resolved by the deepest ISO 15 $\mu$m surveys, and a M82-like spectral energy distribution (SED) at z~0.8−1 can match the broader CIB in shape quite well, except longward of ~200 $\mu$m where higher redshift and/or cooler sources are also required. ISOPHOT 60 $\mu$m to 170 $\mu$m observations resolve only 5−10% of the CIB directly (Dole et al. 2001), with typically z<0.3 and $L_{IR}$~$10^{9-11}L_\odot$, and with some relatively cool IR SEDs (Chapman et al. 2002). AGN are thought to contribute 10−20% of the mid-IR CIB (Fadda et al. 2002; Franceschini et al. 2002). The fraction of IR-luminous systems hosting AGN is of much interest in light of Chandra and XMM discoveries that the hard X-ray background is dominated by obscured AGN which peak at redshift ~0.7−1 (Hasinger 2003).

In the submm very luminous ultraluminous IR galaxies (ULIRGs) at redshifts ~2−4 are surprisingly numerous (Blain et al. 2002; Chapman et al. 2003; Stevens et al. 2003), at least compared to expectations from hierarchical structure formation models (Somerville et al. 2001), though more recent modelling is now beginning to match them (Granato et al. 2002; Balland, Devriendt, & Silk

2003; Lacey et al. 2004, in preparation). AGN could also contribute directly to the luminosity of these systems, decreasing the conflict with hierarchical models; indeed many submm sources with spectroscopy available do show evidence of embedded AGN (Chapman et al. 2003), albeit of unknown power compared to the observed luminosity.

Locally the IR Universe is dominated by quiescent disk star formation and modest starbursts, and ULIRGs are very rare. Most evolution models for the more distant Universe require strong luminosity evolution to z=1 or higher (eg. Chary & Elbaz 2001; Franceschini et al. 2001; Xu et al. 2003; Lagache, Dole, & Puget 2003), with the most extreme evolution rates for ULIRGs to z>2, bringing them into dramatic dominance at early times. Whilst these are usually assumed to be massive starburst systems, it should be noted that dust masses and temperatures are poorly constrained at high redshifts, and the importance of massive cool disks must be considered (Rowan-Robinson 2001; Chapman et al. 2002; Kaviani, Haehnelt, & Kauffmann 2003).

## 2. Stellar Mass Accumulation

Studies of the accumulated mass in stars have been limited to small fields and to the K-band or shorter, and thus the rest-frame optical at high redshift. Dickinson et al. (2003a) and Rudnick et al. (2003) find that ~50% of the stellar mass in the Universe has formed by z~1, most of it since z~3. On the other hand some massive systems may have formed earlier in more monolithic fashion (Cimatti 2003; Pozzetti et al. 2003; Daddi et al. 2003), and the high luminosity ULIRGs at z>2 may be the progenitors of these massive, clustered, spheroids.

The ideal rest observing window for evolved stellar systems is ~1—2 $\mu$m, where the SED of low mass stars peaks and where extinction effects are low; SIRTF's IRAC camera was in part optimized to directly observe evolved stellar populations at their SED peak to high redshift (Simpson & Eisenhardt 1999). SIRTF surveys will dramatically improve our knowledge, not only due SIRTF's supreme sensitivity in this wavelength range, but to large area coverage which will avoid biases due to cosmic variance in the presence of strong clustering on many scales (Berta et al. 2004).

## 3. SIRTF Extragalactic Surveys: Overview

SIRTF (Gallagher 2003) was launched on Aug 25, 2003, into an Earth-trailing orbit carrying a helium-cooled 85-cm telescope and three instruments: the Multiband Imaging Photometer for SIRTF, MIPS (PI G. Rieke; Young et al. 2003), the Infrared Array Camera, IRAC (PI G. Fazio; Hora et al. 2003) and the Infrared Spectrometer, IRS (PI J. Houck; Roellig et al. 1998). SIRTF is expected to have a 3–5 year lifetime. The IRAC imaging array sizes are 256×256, giving FOVs of $5'\times5'$ with pixel size of $1.2''$. The MIPS FOVs are also $5'\times5'$ at 24 and 70 $\mu$m, and $0.5'\times5'$ at 160 $\mu$, while the physical array sizes are 128×128, 32×32 and 2×20 respectively, with pixel sizes $2.6''$, $9.9''$ and $16''$. IRS also has 15 $\mu$m imaging capability, using the 33×45 pixel peak-up array, with an FOV of $1'\times1.2'$ and pixel size of $1.8''$.

Table 1. SIRTF Extragalactic Surveys

| Survey | Pre-launch sensitivity, 5$\sigma$, w/o confusion | | | | | | | Area |
|---|---|---|---|---|---|---|---|---|
| | 3.6 | 4.5 | 5.8 | 8 | 24 | 70 | 160 | |
| | $\mu$Jy | $\mu$Jy | $\mu$Jy | $\mu$Jy | mJy | mJy | mJy | deg$^2$ |
| SWIRE | 7.3 | 9.7 | 27.5 | 32.5 | 0.45 | 2.75 | 17.5 | 65 (7 fields) |
| FLS | 12 | 15 | 43 | 49 | 0.46 | 3.0 | 24.7 | 5 |
| GTO-wide | 8 | 11 | 32 | 38 | 0.5 | 3.0 | 25 | 9 |
| GTO-deep | 2 | 4 | 11 | 16 | 0.11 | 1.0 | 15 | 2.5 (6 fields) |
| GTO-ultra | 0.6 | 1.0 | 3.5 | 4.8 | 0.035 | 0.7 | - | 0.3 (0.02 MIPS) |
| GOODS-deep | 0.15 | 0.25 | 0.8 | 1.2 | 0.02 | - | - | 0.08 (2 fields) |
| GOODS-ultra | 0.1 | 0.15 | 0.45 | 0.65 | - | - | - | 0.014 |
| Confusion | 3–7 | 3–7 | 3–6 | 3–8 | 0.15 | 10 | 70 | |

The SIRTF extragalactic surveys will directly measure far-IR luminosities of the major galaxy populations to z$\sim$0.5$-$1, when the $\sim$80$-$120 $\mu$m peak of the FIR SED of typical starbursts/disk systems passes out of the 70 $\mu$m and 160 $\mu$m filters. Mid-IR emission will be traced to greater redshifts, and may be used to a certain extent as an $L_{IRbol}$ estimator (Papovich & Bell 2002). SIRTF will excel, in particular, as an AGN "machine", due to its superb sensitivity at 8 and 24 $\mu$m coupled with the mid-IR rest wavelength peak of AGN dust tori SEDs. At 160 $\mu$m, SIRTF will chart new ground since its sensitivity at this wavelength is unprecedented.

Details of the major SIRTF surveys are given in Table 1: the First Look Survey (FLS); the Guaranteed Time Observer (GTO) surveys; and 2 of the 3 extragalactic Legacy surveys: The SIRTF Wide-area InfraRed Extragalactic survey, SWIRE (PI C. Lonsdale; Lonsdale et al. 2003); and the Great Observatories Origins Deep Survey, GOODS (PI M. Dickinson; Dickinson et al. 2003b). Also in Table 1 are typical estimates of the flux level at which source confusion will cause the source completeness to drop below 90% (Vaisanen, Tollestrup, & Fazio 2003; Dole, Lagache, & Puget 2003; Shupe et al. 2004). All the surveys are expected to be confusion-limited at 160 $\mu$m, and possibly also 70 $\mu$m. The shortest IRAC bands may become confusion-limited for the GTO deep survey, and the remaining bands may become confused before the full depth of the GTO-ultra and GOODS surveys is reached. Thus SIRTF confusion limits will be reached in all bands in one survey or another. The fraction of the CIB that might be resolved by SIRTF is about 20% at 160 $\mu$m, $\sim$50% at 70 $\mu$m and perhaps $\sim$70% at 24 $\mu$m (Lagache et al. 2003).

All the SIRTF survey fields have been selected to optimize coverage of previous extragalactic surveys and to minimize noise from cirrus and zodiacal emission. Even the shallowest tier (the GTO wide survey in the Bootes region, the FLS survey and the SWIRE Legacy survey, which together cover $\sim$80 deg$^2$ in all IRAC & MIPS imaging bands) reaches cosmological distances owing to the superb sensitivity of SIRTF. The goals of these wide surveys are to map dusty galaxies and evolved stellar populations to z>1 across scales of 100 Mpc or more, and to determine luminosity functions in 100s of independent volume cells, detecting over $10^6$galaxies and AGN. Of particular importance is the ability

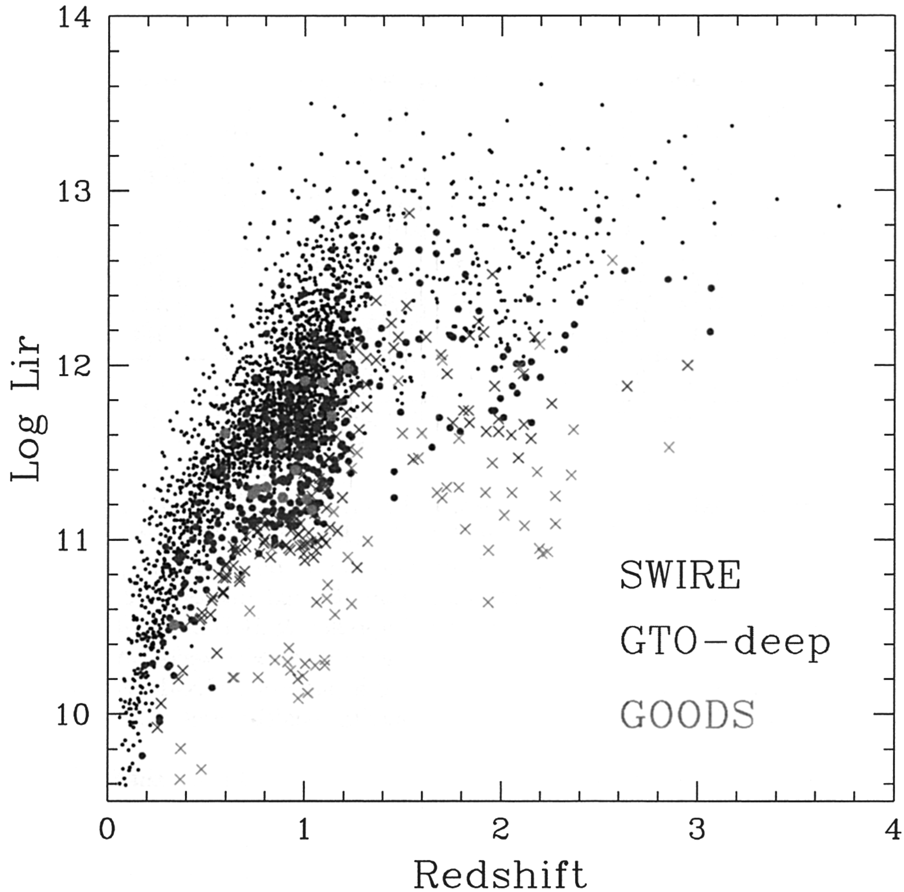


Figure 1. Predicted infrared luminosity vs. redshift for simulated galaxy populations (Xu et al. 2003) detected at 24 $\mu$m within ~1/65 of the total area covered by each of three SIRTF surveys. The subset of the sample detectable in the presence of confusion noise at the level estimated in Table 1 is shown with solid symbols. In the complete absence of confusion noise, the sample shown with crosses would also be detected by GTO-d and GOODS. SWIRE is not expected to be significantly affected by confusion at 24 $\mu$m. Based on pre-launch sensitivity estimates. The boundaries running from bottom left to top right represent sensitivity limits, and the irregularities in them are due to spectral features passing though the bandpasses.

to measure clustering accurately on many size scales in relation to the dark matter density field. The suite of 9 different fields provides robust protection against cosmic variance, from local to cosmological distances. An intermediate tier is provided by coordinated IRAC and MIPS GTO deep surveys in 6 different regions, each $25' \times 60'$ in size except the 2 deg long Groth strip which is extended in order to sample several correlation lengths at z~1. The deepest tier comes from the GTO ultradeep survey and the GOODS Legacy survey, the ultimate depth of which depends on the confusion noise they confront. GOODS will not

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observe at 70 or 160 $\mu$m, and at 24 $\mu$m is contingent on performance relative to the GTO ultradeep program. The goals of GOODS are to determine stellar masses from the IRAC data to ~1 mag fainter than L* at z~3, and to reach L* at z~5. At 24 $\mu$m, GOODS aims to detect the 7.7 $\mu$m PAH feature at z~2 to the same luminosity as the ISO 15 $\mu$m data achieved in the HDF at z~1, and to detect "ordinary" Lyman Break Galaxies at z~2.5 (Dickinson et al. 2003b). GOODS observes two separate fields (HDFN & Chandra DFS) to guard against cosmic variance.

Extensive X-ray to radio complementary programs are underway for all SIRTF surveys, necessary for fully constraining the accretion and star formation histories of the Universe, and for optical/NIR identifications, photometric redshifts, morphologies and environments. However current X-ray, NIR and radio sensitivities can match neither the width nor the depth of the shallowest/deepest SIRTF surveys in reasonable integration times, and some faint luminous IR sources will also remain unidentified in the optical. Thus much multiwavelength follow-up of SIRTF samples will await future large observatories, from JWST to ALMA (Atacama Large Milimeter Array) and SKA (Square Kilometer Array).

The third extragalactic Legacy program, SINGS (SIRTF Infrared Nearby Galaxy Survey; PI R. Kennicutt; Kennicutt et al. 2003), will not directly observe the distant Universe, but will provide vital local "anchor points" for it by characterizing star formation in 75 local galaxies, tracing the processing of energy from young stars through the dusty ISM. Numerous smaller GTO programs will also contribute detailed studies of other known galaxies and AGN, from the local Universe to the most distant known objects; the best resource for exploring the GTO program is the Reserved Objects Catalog (http://sirtf.caltech.edu/SSC/roc/).

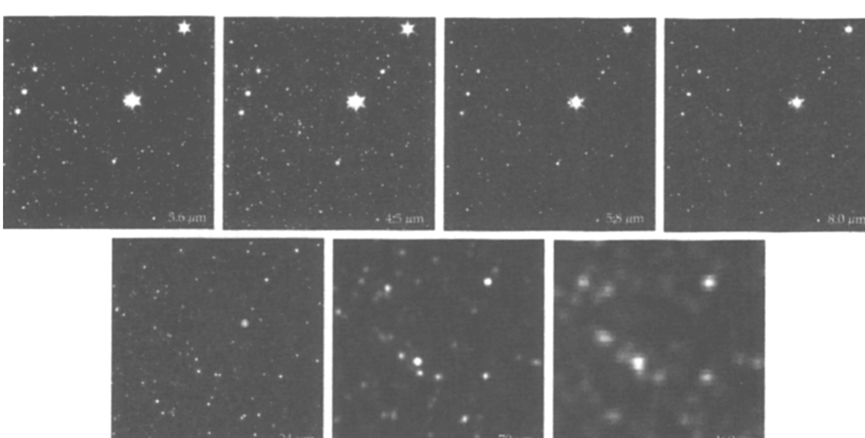

Figure 2. Simulation of SWIRE images in the 7 SIRTF bands (Xu et al. 2003 model); 10′ FOV.

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## 4. SWIRE: The SIRTF Wide-area InfraRed Extragalactic Survey

SWIRE is the largest of the six SIRTF Legacy Surveys (~900 hours), surveying approximately 65 square degrees in all 7 SIRTF imaging bands. A current description of the SWIRE Survey is given by Lonsdale et al. (2003) and on the SWIRE Web Pages: http://www.ipac.caltech.edu/SWIRE. Table 1 lists the survey sensitivities.

The Survey will cover seven high-latitude fields, selected to be the most transparent, lowest-background wide-area (> 5 deg$^2$) fields in the sky. The fields, covering between 5 and 15 deg$^2$, including previously well-known IR extragalactic survey fields (e.g. Lockman Hole and 3 ELAIS ISO Survey Fields) and x-ray fields (Chandra Deep Field South and XMM Large Scale Survey), are shown in Table 2.

Table 2. SWIRE Survey Fields

| Field | Center (J2000) RA | Dec | Area (sq deg) | I(100 $\mu$m) (MJy/Sr) | Prob. Obs. Date |
|---|---|---|---|---|---|
| ELAIS S1 | $00^h38^m\ 30^s$ | $-44°\ 00'$ | 14.6 | 0.42 | Jun/Jul 04 |
| XMM-LSS | $02^h21^m\ 20^s$ | $-04°\ 30'$ | 9.2 | 1.3 | Jul/Aug 04 |
| Chandra-S | $03^h32^m\ 00^s$ | $-28°\ 16'$ | 7.8 | 0.46 | Aug/Sep 04 |
| Lockman | $10^h45^m\ 00^s$ | $+58°\ 00'$ | 14.4 | 0.38 | Apr/May 04 |
| Lonsdale | $14^h41^m\ 00^s$ | $+59°\ 25'$ | 6.9 | 0.47 | Feb 05 |
| ELAIS N1 | $16^h11^m\ 00^s$ | $+55°\ 00'$ | 9.2 | 0.44 | Jan 04 |
| ELAIS N2 | $16^h36^m\ 48^s$ | $+41°\ 02'$ | 4.7 | 0.42 | Jun/Jul 04 |

The SWIRE science goal is to enable fundamental studies of galaxy evolution in the infrared for $0.5 < z < 3$:

- evolution of star-forming and passively evolving galaxies in the context of structure formation and environment.
- spatial distribution and clustering of evolved galaxies, starbursts, and AGN.
- the evolutionary relationship between galaxies and AGN and the contribution of AGN accretion energy to the cosmic backgrounds.

Galaxy evolution models which match the IRAS/ISO galaxy counts at all wavelengths from 7–850 $\mu$m as well as the CIRB (Xu et al. 2003), predict that SWIRE will detect of the order of 2 million galaxies — spheroids and evolved stellar systems with IRAC, and active star-forming systems with MIPS. SWIRE will also detect about 25,000 classical AGN, and an unknown number, perhaps several times as many, dust-enshrouded AGN.

Recent estimates of the "Universal Star-formation History (SFH)" suggest that the bulk of cosmic evolution occurs between redshifts $0.5 < z < 3$, the redshift interval for which SWIRE is optimized. The median SWIRE redshift for starbursts is predicted to be $\langle z \rangle \sim 1$, where many estimates find a peak in the SFH; luminous infrared galaxies will be detected by SWIRE out to $z \sim 3$.

Previous estimates of the SFH have varying, frequently large, and uncertain corrections for extinction. SWIRE will measure the star-formation rates and modes as a function of redshift and environment over this critical epoch.

A key element in the SWIRE Survey design is to enable galaxy evolution studies in the context of large-scale structure/environment. One of the SWIRE Survey fields covers 9 $deg^2$ of the XMM-LSS Survey (Pierre et al. 2004) so that the infrared galaxy census may be directly tied to the presence of rich x-ray clusters to $z > 1$. SWIRE will sample several hundred 100 Mpc-scale co-moving volume cells, enabling a variety of large-scale structure measures from correlation functions, power spectra, and counts-in-cells for direct comparison with model calculations. SWIRE's measures of the star-formation as a function of environment will be important input for CDM simulations which have been exceedingly successful in simulating the development of structure in the early Universe, but perhaps less so in simulating galaxy evolution within that structure owing to the complexity of the physics of star formation (e.g., Kay et al. 2002).

The similarities of many AGN SEDs in the mid-far infrared suggests that SWIRE will be less biased with respect to AGN types and ages than many other surveys, enabling a more complete census of AGN out to $z > 1$. Although the detection rates should be unbiased, the similarity between the SEDs of obscured AGN to those of starbursts, and the extreme optical depths will make *identifying* the obscured AGN population very challenging. Low-frequency radio surveys will, of course, identify radio-loud AGN, but these make up only 10–15% of the AGN population. For this reason the XMM-LSS Survey, along with current and planned deeper surveys in hard x-rays, will be vital to identifying SWIRE AGN.

## 5. Supporting Observations

An aggressive program of ground-based optical, near-infrared and radio observations is planned in support of the SWIRE Survey and we are actively pursuing other programs with HST, Chandra, XMM and GALEX. As already described Chandra and XMM Surveys will be important for discovering the obscured AGN population. SWIRE has entered into cooperation with the GALEX team so that the SWIRE fields will be included in the GALEX Deep Survey.

The SWIRE Optical-Near Infrared goal is to obtain moderate-depth optical multi-band ($g' \sim 25.7$, $r' \sim 25$, $i' \sim 24$; Vega magnitudes, $5\sigma$ for a $2''$ galaxy) data for the entire Survey area. At these limits we expect to detect approximately 2/3 of SWIRE sources detected by both MIPS and IRAC. The ELAIS N1, N2 fields have been imaged to somewhat shallower limits ($r' \sim 24$) as part of the INT Wide Field/ELAIS Surveys and have now been released (Rowan-Robinson et al. 2004). Efforts continue to push deeper in EN1/2 in the optical and into the near infrared as part of UK SWIRE-related Programs. An extensive program for observations of ELAIS S1 is being undertaken at ESO. Optical imaging of the Lockman, Lonsdale and CDFS fields are being undertaken at KPNO and CTIO with the Mosaic cameras and at Palomar with the $200''$ Large Format Camera.

Three major SWIRE radio surveys are planned. The median 20 cm flux density predicted for SWIRE starburst galaxies is $\sim$50 $\mu$Jy — too faint to survey the entire area to this depth. We have therefore carried out a deep pencil-beam VLA Survey (F. Owen, PI) and are planning two extended shallow surveys.

- SWIRE Lockman Deep VLA Survey — 3 $\mu$Jy rms @ 20 cm; $\alpha = 10^h 46^m$ $\delta = +59° 01'$; 30′ VLA primary beam is the deepest VLA field at 20 cm.
- Cosmic Windows VLA Survey — 50 $\mu$Jy rms @ 20 cm in the combined fields of SWIRE, GALEX and XMM-LSS which are accessible to the VLA. This Survey is to be proposed (J. Condon, PI).
- Australia Telescope Compact Array Survey — 3 deg$^2$ in each of the ES1 & Chandra-DFS SWIRE fields, reaching 10 $\mu$Jy rms @ 20 cm (B. Boyle, PI).

Finally, in addition to the XMM-LSS coverage of our XMM field and individual existing Chandra/XMM fields in CDFS, Lockman, EN1 and EN2, SWIRE is carrying out a large Chandra survey of our Lockman Deep Radio-Optical Field:

- Chandra Lockman Survey — 630 ks (9 × 70ks ACIS pointings) is being devoted in Cycle 5 to deep imaging ($\sigma \sim 10^{-15}$ erg cm$^{-2}$ s$^{-1}$).

The SWIRE Legacy Survey is a community survey; the large dataset which is being accumulated reflects the synergies between the Legacy program and other major public surveys. With a couple of million galaxies and several tens of thousands of AGN, many with redshift estimates and SEDs from x-ray to radio, SWIRE's SIRTF database will be released to the community through the SIRTF Science Center (SSC) Archive with the ancillary data released through IPAC's Infrared Science Archive (IRSA).

## 6. Beyond SIRTF

In the next decade we can look forward to ASTRO-F and WISE, all-sky mapping missions in the near- to far-IR. ASTRO-F is a Japanese-led mission, observing from 9–170 $\mu$m and due to launch in Spring 2005 (Pearson et al. 2003). The Wide-field Infrared Survey Explorer, WISE (E. Wright, PI), is currently in extended review at NASA for launch around 2008. It will survey the entire sky at 3.5, 4.7, 12 and 23 $\mu$m with 3–6 orders of magnitude better sensitivity than previous allsky surveys. Carrying a cold 50-cm telescope in sun-synchronous orbit it will deliver over $10^6$ images over the entire sky and catalogs of $\sim 5 \times 10^8$ objects. WISE will map the local Universe to z$\sim$0.6, and has enough volume to detect ULIRGs 16 times more luminous than SWIRE to z$\sim$4.

Herschel and Planck launch together towards the end of the decade. Herschel, with a 3.5-m mirror (Pilbratt 2001), will provide imaging and spectroscopy, reaching submJy photometric sensitivities for deep surveys at 250, 350 and 500 $\mu$m with SPIRE, and at 70, 110 and 170 $\mu$m with PACS. Given the larger mirror size compared to SIRTF, Herschel will be able to provide similar sensitivities and resolutions as SIRTF at complementary longer wavelengths. PACS may resolve $\sim$80% of the CIB at 100 $\mu$m, determining with great accuracy the nature of the dominant population (Lagache et al. 2003). SPIRE will not be able to resolve a large fraction of the longer wavelength background, but will provide sensitive measurements in the rest-frame far-IR to z$\sim$3 or higher. The brighter Planck all sky survey at 350 $\mu$m – 20 GHz (http://sci.eso.int/planck) will be very sensitive to rare and luminous submm/mm sources, especially cool dusty objects, extending the IRAS, ASTRO-F & WISE all-sky views of the Universe to much longer wavelengths.

## 7. Summary

ISO resolved a large fraction of the mid-IR CIB, showing it to be dominated by LIRGs at z$\sim$0.8, while at longer wavelengths, luminous, rare, distant systems are important. Star formation is the dominant energy source, with important contributions from heavily dust-obscured AGN. Dust temperatures are not well constrained at high redshift, raising the possible importance of quiescent star formation in cool disks at early times. NIR studies of evolved systems also show evidence for both slow hierarchical assembly since z$\sim$3, and more rapid formation of massive systems at early times. Each of the SIRTF surveys will trace both evolved stellar populations (with IRAC) and dusty systems (with MIPS) over matched volumes, providing a supreme opportunity to connect the evolution of these populations in time and space. The shallowest SIRTF surveys will have superb volume and area coverage, sensitive to structures on 100s of Mpc and ULIRGs to z$\sim$4, while the deepest studies will trace L* systems to z$\sim$2.5, and reach the confusion limits in all SIRTF imaging bands: 3.6 to 160 $\mu$m. SIRTF may resolve about 70, 50 and 20% of the CIB at 24, 70 and 160 $\mu$m respectively.

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