The Great Observatories Origins Deep Survey

> *"With increasing distance our knowledge fades and fades rapidly. Eventually we reach the dim boundary, the outmost limits of our telescope. The search will continue. Not until the empirical resources are exhausted need we pass on to the dreamy realm of speculation."* Edwin Hubble, Realm of the Nebulae, 1936

Introduction

The Great Observatories Origins Deep Survey (GOODS) is a campaign to unite extremely deep, multiwavelength observations to create a public, legacy data set for exploring the distant universe. GOODS builds upon the deepest existing or forthcoming surveys by the other NASA Great Observatories, Hubble and Chandra, and ESA's XMM-Newton, providing the most sensitive SIRTF observations at mid-infrared wavelengths to study light from stars and star formation in high redshift galaxies. GOODS will make it possible to follow the mass assembly history of galaxies and the nature and distribution of their energetic output - from both stars and AGN - over a broad span of cosmic history. By measuring the discrete source contribution to the sky brightness with unprecedented sensitivity, GOODS will also greatly improve the lower limits to the mid-infrared extragalactic background light, the integral record of cosmic emission. GOODS probes the faintest flux limits in the SIRTF observing program for the first year, with a unique combination of depth, multi-wavelength coverage and area, and paves the way for future surveys with telescopes operating at similar or longer wavelengths, including FIRST, ALMA and NGST.

The survey area is divided into two sightlines, one in each celestial hemisphere, in the vicinity of the Hubble Deep Field North (HDF-N) and the Chandra Deep Field South (CDF-S). The total SIRTF coverage is approximately 330 arcmin^2, with a depth sufficient to provide rest-frame optical and near-IR photometry for thousands of objects at $z > 2$. The combination of X-ray and mid-infrared data will permit a census of emission from massive central black holes, both obscured and unobscured by dust, and will provide the means to distinguish between AGN and star formation as the energy sources powering mid- and far-infrared emission.

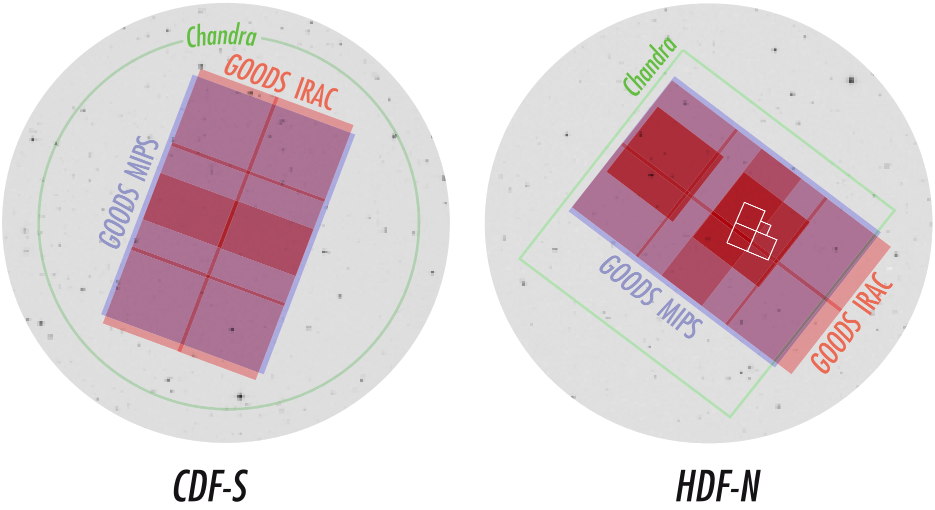

Fig 1. GOODS layout. The two Chandra fields (in green) will each have 1 Msec of exposure. The HDF-N (white chevron) has ~700 ksec of HST WFPC2 and NICMOS data. Red overlays show the regions covered by the IRAC observations at various depths, from 25 to 100 hours. Blue overlays show the MIPS 10 hour exposure regions. The field orientations are chosen to allow efficient tiling with all 4 IRAC bands, accomplished by observing the field twice, with a six month interval between the two epochs.

GOODS will observe these fields with IRAC at 3.6-8.0 μm with uniform 25 hour exposure times, suitable for detecting the rest-frame near-infrared light from ordinary galaxies (e.g., the progenitor fragments of the Milky Way) out to z~4 or beyond. A pair of smaller, ultradeep IRAC fields with 75-100 hour exposure time is also planned within the HDF-N GOODS region, contingent upon on-orbit demonstration of telescope and instrument performance and source confusion. The program also calls for uniform 10 hour observations with MIPS at 24 μm, also contingent upon in-flight demonstration that these data will reach significantly deeper flux limits than the 1200 second exposures already planned for these fields by the MIPS Guaranteed Time Observer (GTO) program. The GTO survey will complete the SIRTF census by observing these fields to the confusion limit at 70 and 160 μm.

The Assembly of Galaxies

How did galaxies grow over time? One observational key to answering this question is to measure the distribution of stellar masses and star formation rates (SFRs) for galaxies as a function of time, over the broadest possible range of redshift. In principle these quantities can be inferred from the luminous output of galaxies using observations at the most suitable wavelengths. To date, most studies have tried to estimate moments of this distribution such as the comoving SFR density vs. redshift, or the stellar mass distribution and its evolution (imperfectly measured via optical luminosity functions). GOODs will provide a major step toward measuring the full distribution function $f(M, \dot{M}, t)$ of stellar mass and SFR over cosmic time. The following key areas will benefit from GOODS data:

Stellar masses and populations. The rest-frame near-infrared light from galaxies most nearly traces the integrated stellar mass because of the smaller *M/L* variations with stellar population age and the greatly reduced effects of dust obscuration. Locally, near-infrared luminosity correlates well with dynamical mass in disk galaxies. At z » 1, rest-frame infrared light shifts beyond the limits of ground-based observations, but may be sampled by SIRTF IRAC data at 3.6-8.0 μm, where we may measure rest-frame 2 μm light from ordinary Lyman break galaxies (LBGs) at z=3 and 1 μm light out to z=7, given sufficiently deep data. The 25-hour GOODS IRAC exposures are designed to detect L^*, z=3 Lyman break galaxies at 8 μm, and the smaller ultradeep fields reach similar objects at z=5 or greater. Photometry from rest-frame UV to IR wavelengths can be used to determine the stellar population properties and mass-to-light ratios of distant galaxies, measuring the stellar mass function of galaxies throughout most of cosmic history.

Star formation. Ultraviolet, mid- and far-infrared, sub-mm, radio, and Balmer line observations all provide windows on star formation at high redshift, both obscured and unobscured by dust. All correlate with star formation and bolometric luminosity to different degrees, and only by studying multiple indicators *for the same galaxies* will we gain a comprehensive picture of high-z star formation. The GOODS 24 μm observations are designed to reach rest-frame 7 μm luminosities at z~2 similar to those probed by the deepest ISO 15 μm surveys at z~1, and to detect the reprocessed PAH emission from relatively ordinary Lyman break galaxies and “LIRGs” with L(FIR) ~ 10^{11} $M_\odot$ /year at these redshifts. GOODS will also provide extremely deep optical imaging for measuring rest-frame ultraviolet light from distant, star forming galaxies, and the fields have been or are being surveyed at radio and sub-mm wavelengths.

Origin and Evolution of the Hubble Sequence. Combined SIRTF measurements and HST imaging will establish the relationships between stellar populations, masses, star formation rates, and galaxy sizes and morphological types.

Evolution of the galaxy "red envelope". GOODS data will measure the space density and spectral evolution of red objects to z~5, separating "passive" ellipticals from dust-obscured starbursts via mid-infrared measurements and infrared spectroscopy. At z>2, we will learn whether actively star-forming galaxies contain older stars, and whether there are massive, quiescent galaxies that have been missed by earlier surveys.

Identification of objects at z>5. A few galaxies have been spectroscopically confirmed out to nearly z=6, and a few remarkable objects have been identified as photometric candidates at still higher redshifts. Until NGST, only SIRTF can measure the rest-frame optical emission from such objects to test these redshift estimates, determine spectrophotometric properties, and constrain space densities.

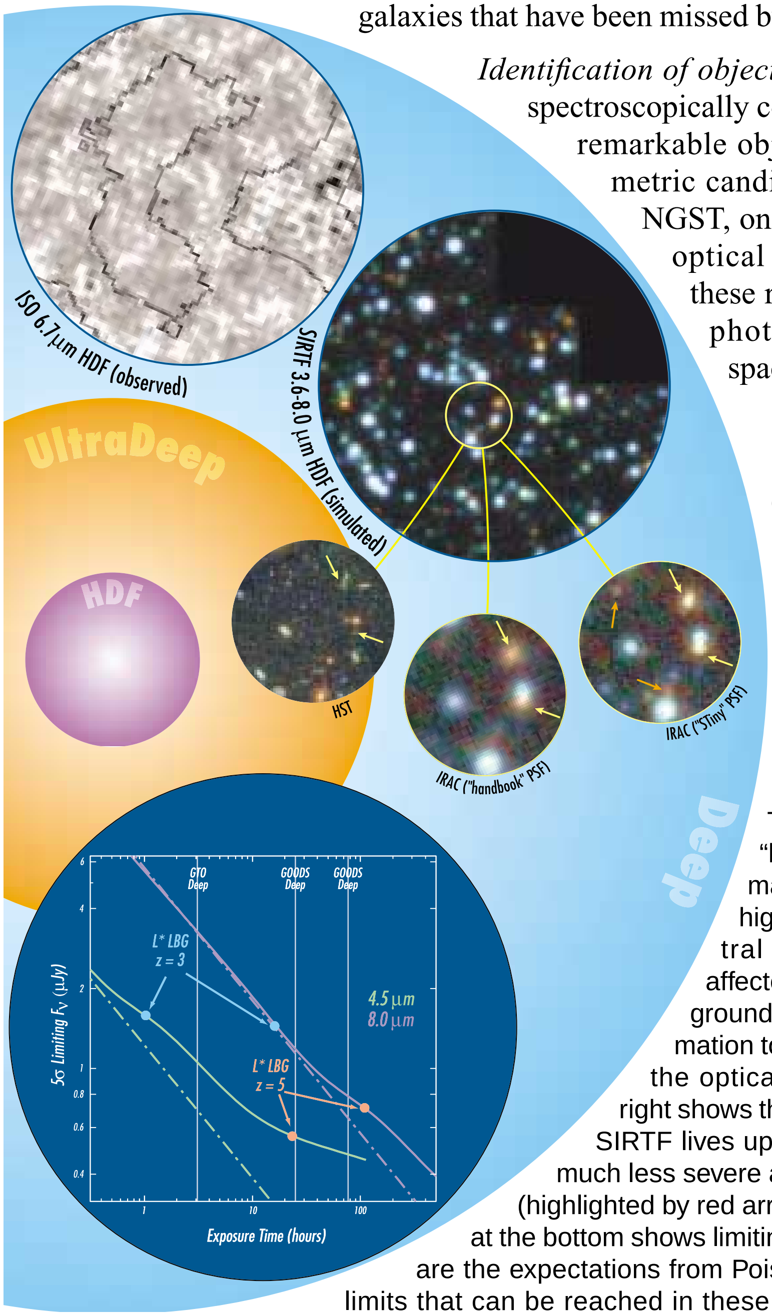

Fig. 2. Simulated ultradeep IRAC data. Near the top, the deep ISO 6.7 mm image of the HDF-N is compared to a simulated IRAC image with 100 hours exposure, using the SIRTF handbook PSF and background noise parameters. The small insets show the WFPC2 HDF (a color composite from optical images) and simulated IRAC three-color images, oversampled using extensive dithering and the "drizzle" technique. The left IRAC image uses the nominal "handbook" PSF, with two galaxies at *z*~3 marked, and shows the ease of identifying high-redshift galaxies via the 1.6 mm spectral inflection. While these galaxies are affected by crowding, higher resolution HST or ground-based images allow accurate flux information to be extracted by fitting profiles based on the optical image parameters. The inset on the right shows the image quality that might be achieved if SIRTF lives up to its early ground testing. Crowding is much less severe and several faint *z* > 4 galaxy candidates (highlighted by red arrows) become easily detectable. The plot at the bottom shows limiting flux vs. exposure time. Dashed curves are the expectations from Poisson statistics. The solid curves are the limits that can be reached in these images using prior information on the source positions and profiles from other sources. The circles in the background are scaled to the relative areas of the WFPC2 HDF and the GOODS Deep and Ultradeep fields.

Source confusion can be an important factor for these deepest SIRTF observations. Information on source positions and spectral energy distributions at other wavelengths and with higher angular resolution provides a powerful means to help "deconfuse" SIRTF data (Fig. 2). The GOODS team is developing techniques to deal with crowded images which should be of general use to the SIRTF community.

Active Galactic Nuclei: the Growth of Giant Black Holes

Massive central black holes are a common, perhaps ubiquitous, feature of galaxies and may play an important role in their formation, evolution and energetic output and in cosmic reionization. As with the stellar content of galaxies, understanding the evolution of massive black holes requires a census of their numbers and masses as a function of cosmic time.

Accretion onto black holes makes them visible as Active Galactic Nuclei (AGN), which are luminous enough to be traced out to very high redshift. But AGN are particularly likely to be obscured by dust. According to the current AGN paradigm, for some lines of sight, dust in a torus or warped disk may obscure the bright optical, ultraviolet and soft X-ray “type 1” emission produced by the central engine, resulting in so-called “type 2” AGN. Infrared studies of nearby Seyfert galaxies have confirmed this geometric relation at low redshift, but very few obscured AGN are known beyond z~0.3. They may indeed be rare (e.g., if the obscuring torus evaporates when accretion rates are large), but it is equally likely that obscured AGN have been overlooked because most surveys are biased against finding them. A better census comes from combining deep infrared and hard X-ray surveys, along with optical or near-infrared spectroscopy to measure redshifts. Although hard X-rays can penetrate most obscuring dust columns, most of the AGN luminosity is actually re-radiated at infrared wavelengths. Hard X-ray emission can be used to distinguish AGN from the far more numerous starburst galaxies in mid-infrared surveys.

With SIRTF’s unprecidented combination of sensitivity and angular resolution, we may search for obscured sources at the AGN epoch (z~2). The expected number of type 2 AGN detectable in the GOODS data set ranges from 0, if the obscuring torus does not exist at high redshift or luminosity, to ~60 for estimates still compatible with the X-ray background and other integral constraints. GOODS data will help to determine the ratio of obscured to unobscured AGN at this critical epoch, and provide a rich sample of objects and a library of multiwavelength data that will enable further studies of the properties of massive black holes and their relation to galaxy evolution.

Source counts and the Extragalactic Background Light

The infrared extragalactic background light (EBL) is an integral record of the emission, absorption and re-radiation of photons over cosmic history. It provides a valuable constraint on theories of galaxy formation and evolution. The EBL at near- and mid-infrared wavelengths consists in part of a discrete source component due to redshifted radiation from stars and hot dust in individual galaxies. In principle there may also be an isotropic, diffuse component from exotic sources such as decaying particles, early “Population III” stars, or primordial black holes.

GOODS will measure the discrete source component of the EBL at 3.6-24μm with unprecidented sensitivity via a combination of straightforward number counts, fluctuation analyses, and other techniques. The IRAC measurements trace the predicted “downside” of the stellar component of the EBL, whose energy density is expected to fall off beyond an expected 1-2μm peak, while 24 μm measurements trace the EBL “upswing” due to energy from star formation and active nuclei that is absorbed and reradiated by dust. These measurements will serve as a constraint on evolutionary models, and may also be compared both with measurements of (and upper limits on) the integrated EBL derived from other methods (e.g., COBE/DIRBE, IRTS, and from TeV gamma ray propagation).

Supporting Observations and Data Products

The GOODS fields are already the most data-rich portions of the sky for studying the distant universe, with extremely deep X-ray and radio data, sub-mm observations (for HDF-N), extensive optical and near-infrared imaging, and a wealth of faint galaxy spectroscopy. The SIRTF observations will further enrich this collection, and will be supplemented by extensive committments of support from ESO and NOAO. NOAO observations will provide very deep, wide-field optical (UBVRI) and near-infrared (JHK) imaging over the HDF-N GOODS field with the MOSAIC and FLAMINGOS instruments. ESO, will provide (subject to review and approval) similar imaging with VLT and NTT instruments, and an extensive campaign of spectroscopy with the high-multiplex spectrographs VIMOS and FORS-2. This will supplement ongoing ESO spectroscopic surveys of Chandra X-ray sources and K-band selected galaxies. The survey will target especially color- and photometric-redshift selected classes of high redshift galaxies that are particularly interesting for study with SIRTF, including star-forming galaxies at $z \sim 1$ and $z > 2$ (the Balmer and Lyman break objects), early-type galaxies and “extremely red objects” at $z \sim 1$, and (when the SIRTF data are in hand) a sampling of IRAC and MIPS-selected galaxies of various sorts. A pilot program is also planned for kinematic spectroscopy of the most luminous galaxies at all redshifts, in order to connect stellar masses from SIRTF to the dynamical masses of dark matter halos.

In the spirit of the Legacy program, all GOODS data products from all facilities will be made public, enabling a wealth of research opportunities for the astronomical community. Survey products will include:

- Individual SIRTF images, optimally calibrated via our post-pipeline processing.
- Enhanced calibration files and models, including improved flat fields resulting from self-calibration, patterns for bias drifts, and other quantitative descriptions of instrument characteristics.
- Full-field coaligned oversampled mosaics. Separate images for Deep and Ultradeep regions and for different epochs to identify variable/transient phenomena. Noise, depth, and exposure maps for each image.
- Source catalogs obtained via classic filtering methods (smoothing, fitting, wavelets), with positional and shape information, multi-band photometry, and common-mask colors.
- Panchromatic source catalogs derived via deconfusion techniques, with matched multi-band photometry. Error estimates including blending and covariance between nearby sources.

Data release is planned in three phases. The first SIRTF data products will appear three months after each SIRTF data taking epoch and will represent a “best effort” at combined SIRTF image mosaics. Improved versions of the complete, re-calibrated combined mosaics at all wavelengths will be available three months after completion of the entire SIRTF observing program. Second-generation reprocessing of the SIRTF data will be carried out if necessary with release six months to a year later. A similar release plan applies to the associated groundbased data.