EXTRAGALACTIC EXPLORATION WITH SIRTF

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Abstract

This paper summarizes the status of the *Space Infrared Telescope Facility - SIRTF. SIRTF* will be the first cryogenically-cooled space observatory instrumented with large-format, state of the art infrared detector arrays. *SIRTF* will complete NASA's family of Great Observatories and also serve as the first major scientific and technical step in the Origins program. It will be launched in 2001, carrying a complement of imaging and spectroscopic instrumentation. More than 75% of the observing time on *SIRTF* will be available to the general scientific community. We review *SIRTF*'s potential contributions to extragalactic astronomy and show how *SIRTF* will build on the major scientific advances being made in this field by *ISO*.

1 SIRTF: An Overview

The combination of the intrinsic sensitivity of a cryogenic space observatory with the imaging and spectroscopic power of high-performance, large format infrared arrays is extremely powerful scientifically. This combination led to *SIRTF*'s designation in 1991 by the National Academy of Sciences as the highest priority major new space mission for US astronomy in the 1990's. The system design and the related detector, cryogenic, and optical technology have evolved steadily since then (see Simmons et al, 1996 for a detailed description), and the final development phase for *SIRTF* is to begin in mid 1998, with launch scheduled for December, 2001. Consistent with this schedule, the *SIRTF* team has been completed with the selection of Ball Aerospace to provide the cryogenic and optical systems, and Lockheed-Martin to build the spacecraft and to carry out system integration and test. Project management, system engineering, and science oversight are the responsibility of the Jet Propulsion Laboratory. *SIRTF* will carry three focal plane instruments: the *Multiband Imaging Photometer for SIRTF (MIPS)*, the *Infrared Spectrograph (IRS)*, and the *Infrared Array Camera (IRAC)*. Dr. G.Rieke of the University of Arizona and Dr. J.Houck of Cornell University are the Principal Investigators for *MIPS* and *IRS*, respectively. These two instruments are being built by Ball Aerospace. Dr. G.Fazio of the Smithsonian Astrophysical Observatory is the Principal Investigator for *IRAC*, which is being built at the Goddard Space Flight Center. Data from *SIRTF* will be processed and disseminated to the scientific community through the Infrared Processing and Analysis Center (IPAC), located at the California Institute of Technology. Up-to-date information on the status of *SIRTF* can be found on the *SIRTF* Web Site: http://sirtf.jpl.nasa.gov/sirtf/home.html.

2 A Description of SIRTF

2.1 The SIRTF Facility

SIRTF will be launched by a Delta rocket into an earth-trailing heliocentric orbit. The telescope will be launched warm and cooled when in orbit, while the three focal plane instruments will be cooled by liquid helium at launch and throughout the mission. This new system architecture permits the launch of *SIRTF*'s 85-cm telescope in a lightweight configuration which brings *SIRTF* within the launch capabilities of the Delta. The cryogenic system is based on a 1.4K liquid helium bath which cools the instruments, while the helium vapor produced by the dissipated instrument power will be used to cool the telescope to its operating temperature of ≈5.5K. This vapor cooling supplement the on-orbit radiative cooling, allowing *SIRTF* to achieve an operational lifetime greater than 2.5 years with only 350 liters of liquid helium. *SIRTF* will have a pointing accuracy of a few arcsec and stability of a fraction of an arcsec for long periods. Precision offsets will allow targets to be placed on spectrograph slits with sub-arcsecond accuracy. The chief features of the *SIRTF* mission are summarized in Table 1.

In addition to providing a benign, stable thermal environment the heliocentric orbit has great operational benefits. About one-third of the sky is visible - continuously - at any one time, as SIRTF can routinely point as close as 80 degrees to the sun and as far as 120 degrees off the sun. Targets within this angular range can be observed for a minimum of 40 days consecutively. Of course, in the heliocentric orbit there are no eclipses and no need for Earth avoidance maneuvers. The only complications are in the telecommunications arena, as in this orbit, SIRTF drifts slowly away from the Earth, reaching a distance of ≈0.2 au in 2.5 yr. Downlink is accomplished using a high gain antenna fixed on the bottom of the spacecraft; spacecraft body pointing is used twice per day to point the antenna at the Earth so that stored data can be sent down via the Deep Space Network.

2.2 SIRTF Instrument Characteristics

Although the three *SIRTF* instruments have differing functional capabilities and scientific niches, there are important commonalities among them. Most notably, each makes extensive use of large-format infrared detector array technology which is now available to the scientific community. In addition, amongst the three of them there is only one moving part - the scan mirror in *MIPS*. There are no filter wheels or grating mechanisms in *SIRTF*. All instrument fields of view are illuminated simultaneously (although only one instrument takes data at a time). As a result, the *SIRTF* user is presented with a restricted set (≈8) of operational modes, which simplifies and reduces the cost of operations. The properties of the three instruments are the following:

1. *MIPS*. *MIPS* provides mapping and imaging at wavelengths of 24, 70, and 160μm and low (R$\sim$20) resolving power spectrophotometry from 50 to 100μm. The principal imaging

Table 1: SIRTF Mission Characteristics

Lifetime		>2.5yr
Aperture		85 cm
Orbit		Heliocentric, 1au
Diffraction Limit		6.5 μm
Image Size		$\approx$ 1.5 arcsec
Pointing		
	Accuracy	5 arcsec (1-σ)
	Stability	0.3 arcsec (1-σ)
	Offset Accuracy	0.4 arcsec (1-σ)
Telescope Temperature		<5.5K
Wavelength Range		
	Imaging, Mapping	3.5-160 μm
	Spectroscopy	5-40 μm
	Spectral Energy Distribution	50-100 μm
Planetary Tracking Rate		up to 0.1 arcsec/s

capabilities are provided at 24μm by a 128^2 pixel Si:As array with a 5.3x5.3 arcmin field of view, and at 70μm by a 32^2 pixel Ge:Ga array, also with a 5.3x5.3 arcmin field of view. The imaging sensitivities (*all sensitivities quoted here are 5-σ in 500s*) of these arrays are 240μJy and 1mJy, respectively. For comparison, the IRAS Faint Source Data Base 5-σ limits are $\approx$100mJy and $\approx$500mJy at 25 and 60μm. The 160μm imaging uses a 2x20 pixel array of stressed Ge:Ga detectors, providing a total field of view of 0.5x5.3 arcmin and a sensitivity of 7.5mJy. A single-axis scan mirror is included to modulate the signal on the Germanium detectors and to provide efficient mapping in a "freeze-frame" mode. The scan mirror can be positioned to select the spectrophotometry mode of the large Ge:Ga array (sensitivity is 3.5mJy) and also to select a higher magnification optical path which reduces the field of view of this array to 2.6x2.6 arcmin. This mode provides critical sampling of the 70μm image, while the images at 24 and 160μm are critically sampled in the configurations described above. At each wavelength, it should be possible to boost the resolution of the fully-sampled images by numerical post-processing.

2. *IRS. IRS* provides low and moderate resolution spectroscopy at wavelengths from 5 to 40 μm. The instrument consists of four separate modules. Two of these provide low resolution (R $\approx$ 50) spectroscopy and two provide moderate resolution spectroscopy with R $\approx$ 600. Each of the four modules contains a single 128^2 Si:As or Si:Sb IBC array; at low resolution, a long slit ($\approx$1') permits imaging in the cross-dispersion direction, while in the two moderate resolution modules the array is used in a cross-dispersed echelle mode. Each of the moderate resolution modules covers an entire spectral order in echelle mode, enabling efficient spectroscopy of faint sources and accurate determination of line ratios; for example,*SIRTF* can quickly obtain a complete 5-40μm spectrum of any *IRAS* source. The wavelength ranges of the two low resolution modules are 5-15 and 15-40μm. Order-sorting filters are fixed on the entrance slit to allow selection of the spectral order to be observed by placement of the target on the slit. The sensitivities of these two modules are 550μJy and 1.5mJy, respectively. The wavelength ranges are 10-20 and 20-40μm, and each has a sensitivity of $3\text{x}10^{-18}$ watt/m^2. A portion of the array in the 5-15μm low resolution module is illuminated by a separate optical path providing direct imaging at

12μm; this serves as a peak-up array to facilitate the placing of infrared targets of poorly known position on any of the spectrograph slits in real time. The peak-up array, with a field of $\approx$ 1x1 arcmin, can also be used for photometry at this wavelength.

3. *IRAC*. *IRAC* provides wide-field imaging at four near infrared bands centered at 3.5, 4.5, 6.3, and 8μm. A 256^2 pixel array is used in each band; InSb at 3.5 and 4.5μm and Si:As at 6.3 and 8μm. A dichroic beamsplitter allows the 3.5 and 6.3μm arrays to view the same 5x5 arcmin field of view; an adjacent 5x5 arcmin field is viewed simultaneously by the 4.5 and 8μm arrays. The predicted sensitivities of the *IRAC* arrays are 4,5,20 and 30μJy, respectively, at 3.5,4.5, 6.3, and 8μm.

3 SIRTF Science

The sensitivities quoted above for *SIRTF* promise major advances in capability over previous and current facilities for infrared astronomy, from ground or space. This, together with the highly efficient imaging and spectroscopy which will be capable with *SIRTF*'s wide field, array-based instrumentation, endows *SIRTF* with a high degree of "discovery potential" for uncovering new phenomena in the Universe. This combines with the advances *SIRTF* can make towards the understanding of known astrophysical problems to make *SIRTF* a powerful bridge between NASA's Great Observatories program, represented by *HST*, and the new generation of Origins missions.

The exact scientific programs to be carried out by *SIRTF* will be defined closer to launch, but there can be no doubt that extragalactic exploration will be a major element of *SIRTF* science. Infrared studies of galaxies have exploded since the important comtribution of infrared radiation to the bolometric luminosity of ordinary galaxies - as well as the existence of ultraluminous infrared galaxies - was demonstrated by *IRAS*. More recently, *ISO* has carried out the first extensive infrared spectroscopy of galaxies at wavelengths beyond 3μm and produced exciting new scientific results. At the same time, the exploration of the Hubble Deep Field at near infrared wavelengths and other results from *HST* and from the Keck telescopes have produced new insights into the morphology and stellar populations in distant galaxies at redshifts as great as 3, and spawned estimates of the star-formation history of the Universe. With results continuing to come in from *ISO*, *HST*, and large ground-based telescopes, and with powerful new instruments such as *NICMOS* and *WIRE* (Hacking et al, 1997) about to join the fray, it would be impossible to detail the extragalactic problems which will be of greatest significance at the time of the *SIRTF* launch in 2001. However, we present below a few examples - reflecting in part the current results from *HST* and *ISO* - which illustrate the capabilities *SIRTF* can bring to bear on the problems of extragalactic astronomy. Many of these examples are discussed in greater detail by Werner and Eisenhardt (1995). The capabilities of SIRTF in another key scientific area - planetary science and the exploration of extra-solar planetary systems - are summarized by Cruikshank and Werner (1997).

3.1 Deep Near Infrared Surveys and the HDF

SIRTF can provide our first measurements of redshifted starlight from distant galaxies at wavelength longward of 3um. The IRAC sensitivity and angular resolution permit the detection of L* galaxies at redshift z>3 in all four bands. As the redshift varies from 0 to >3, the diagnostic 1.6 and 2.3μm features seen in the spectra of red giants shift through the IRAC bands, allowing a photometric redshift determination from the position of the galaxy in a color-color diagram (Werner and Eisenhardt, 1995). A possible deep IRAC survey to study the distant galaxy population would cover 0.2 sq degree and reach 10-σ flux levels of 6μJy in each band. Models suggest that the resultant data base could contain $\approx$ 600 L* galaxies with z>3 - and many more at smaller redshifts - separable with the photometric redshift described above. This survey would provide a determination of the evolution of the stellar content of galaxies - and of the galaxy population -with redshift.

Follow on observations of the Hubble Deep Field have already identified a number of galaxies with z>1. Near infrared (JHK) photometry of the HDF (Dickinson and Eisenhardt, 1996) can be combined with the 4 bands measured by HST to produce broad-band spectral energy distributions for HDF galaxies. Extrapolation of these SEDs suggests that many of these galaxies can be measured by *SIRTF*. Note that a single 5x5 arcmin *SIRTF* image covers a much larger solid angle than the $\approx$2x2 arcmin HDF. Of course, the most interesting objects in *SIRTF*'s images of the HDF would be any not seen at shorter wavelengths, which could be representatives of a highly reddened, or highly red-shifted, galaxy population.

3.2 The Star Formation History of the Universe

SIRTF observations of far infrared emission from the galaxies in the HDF will round out the picture of the star formation in this unique slice of the Universe. Rowan-Robinson et al (1997) have studied the HDF using the highly successful *(*ISO) spacecraft (Kessler et al, 1996). Rowan-Robinson et al detected several galaxies in the HDF using *ISO* at 15μm and predicted that they are powered by massive, dust embedded starbursts with energy output peaking near 100μm as observed from Earth. *SIRTF* can provide both improved mid-infrared data on the HDF galaxies and follow up far infrared observations which will directly determine the amount of luminosity being contributed by hidden stars. In addition, *SIRTF*'s science programs might include a survey of several hundred square degrees to flux levels $\approx$1mJy at 70μm, determining the luminosity function of galaxies in the wavelength range where most of their infrared luminosity emerges, and providing a source list for followup exploration with *SIRTF*'s spectrograph. Such a survey would be capable of detecting ultraluminous infrared galaxies such as FSC15307+3252, which has L$\approx$2x$10^{13}L_\odot$, at redshift z>5 - provided that star and dust formation in the early Universe was capable of forming such a luminous and dusty system at such an early epoch.

3.3 Composition, Excitation and Redshifts of Galaxies

SIRTF's spectrograph may play a key role both in determining the redshifts of galaxies found by *WIRE*, by ISO - and by *SIRTF*'s own deep surveys - and in studying the abundances and excitation conditions in these systems. *ISO*'s results have shown that the 5-12μm emission from spiral galaxies is dominated by the broad emission features attributed to aromatic hydrocarbons. The spectral shape of this emission is surprisingly constant from galaxy to galaxy, suggesting its use to determine redshifts of distant galaxies. For example, the starburst galaxy NGC6090 which has L_{ir} = 3x$10^{11}L_\odot$ has been shown by *ISO* (Acosta-Pulido et al, 1996) to have strong emission of this type. *SIRTF* could measure the redshifted aromatic features with high signal-to-noise in this galaxy to beyond z=0.5, and more luminous galaxies could be probed at still greater redshifts. It would also be of great interest to see whether the hydrocarbon features could be seen in the most distant galaxies seen by SIRTF, which should have z>3.

Atomic fine structure lines in the mid-infrared sample ionization states ranging, for example, from NeII to NeVI, and Voit (1992) has shown how these lines of neon and other species can be used to distinguish among various excitation sources for the plasma in a dust-embedded galactic nucleus. Additional results from *ISO* (Moorwood et al, 1996; Rigopolou et al, 1996) have shown the predicted progression in excitation from known AGN to known starburst galaxies, demonstrating the diagnostic value of the infrared lines. Extrapolating from the line intensities measured by *ISO*, the *IRS* on *SIRTF* can distinguish between AGN and starburst excitation in the most luminous infrared galaxies to z>3. *SIRTF* would begin this type of investigation with a selection of sources drawn from the WIRE and *ISO* data bases, and continue by exploring galaxies found in *SIRTF*'s own surveys. *ISO* has returned diagnostic spectroscopy on the nearest AGN's and infrared-luminous galaxies. The combination of improved sensitivity and the multiplex advantage inherent in *SIRTF*'s larger arrays is what allows *SIRTF* to push these explorations to high redshift, allowing a search for evolutionary trends in the excitation mechanisms, physical conditions, and abundance mechanisms in these objects.

4 Community Utilization of SIRTF

At least 75% of the observing time on *SIRTF* will be made available to the general scientific community through a peer-reviewed proposal process. (The remainder of the observing time will be divided between Guaranteed Time Observers and Director's Discretionary Time). Two separate types of community participation in *SIRTF*'s observing programs are envisioned, Legacy Observations and General Observations. Legacy Observations are distinguished from General Observations by the following three criteria:

1. The project is a large, coherent investigation whose scientific goals cannot be met by a number of smaller, uncoordinated projects;
2. The data will be of both general and lasting importance to the broad astronomical community and of immediate utility in motivating and planning follow-on GO investigations with *SIRTF*
3. The data will be placed in a public data base immediately and with no proprietary period

The objective of the Legacy Program is thus not only to do execute excellent science but also to develop data bases upon which *SIRTF* users can base follow-on proposals. This is an essential component to the scientific utilization of *SIRTF*, because of its short life time and high sensitivity. The Legacy programs will be solicited from the general scientific community and the teams selected prior to launch so that the Legacy Observations can begin early in the mission. Depending on the programs proposed and selected, as much as 50-70% of *SIRTF*'s first year on orbit might be devoted to Legacy science. General Observations will constitute the remainder of the community utilization of *SIRTF*. GO selections will take place every nine to twelve months, with the first solicitation prior to launch. In addition, the *SIRTF* archive will be publicly accessible starting about six months after launch, and a funded archival research program will be supported during the mission. The community role in *SIRTF* is being defined by a Community Task Force headed up by R.Gehrz of the University of Minnesota. Refer to the *SIRTF* Web site listed earlier for information on the activities of the task force and on other opportunities for community involvement, and also for a time estimator which provides a prospective SIRTF user an estimate of the wall clock time required for his/her sample SIRTF observing program(s).

5 SIRTF and Future Space Missions

In addition to its great scientific contributions, *SIRTF* will advance and demonstrate technologies which will be critical for the development of subsequent missions for infrared astronomy from space, such as NASA's proposed *Next Generation Space Telescope (NGST)* and ESA's *Planck* and *FIRST* missions. These include:

1. Radiative cooling and high efficiency cryogenic systems
2. Lightweight cryogenic optics
3. Ultrasensitive infrared arrays
4. Operation of an astrophysical observatory in deep space

SIRTF's approaches to these and other key technical challenges are reviewed by Simmons et al (1996).

6 Summary and Conclusions

The technological and scientific revolution begun by *IRAS*, *COBE*, and *ISO* will be continued by *SIRTF*, the first observatory-class mission to combine the intrinsic sensitivity of a cryogenic telescope in space with the scientific power inherent in the new generation of large format infrared array detectors. With the launch of *SIRTF* no more than four years away, and with results from numerous spacecraft and ground-based telescopes to whet our scientific appetities, it is time for prospective users to start thinking seriously about how they can use this powerful observatory to attack the scientific challenges which most interest them. We hope that the spirit of international collaboration which has made *ISO* so successful throughout is carried over to *SIRTF*, and that these users will be drawn from all continents.

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References

[1] Acosta-Pulido,J.A. et al. 1996 *Astr. Astrophys.* **315**, L121

[2] Cruikshank, D.P., and Werner, M.W. 1997, in *Planets Beyond the Solar System and the Next Generation of Space Missions*, ed. D. Soderbloom, ASP Conference Series **119**, in press.

[3] Dickinson, M., & Eisenhardt, P.R.M, see *http : //www.stsci.edu/ftp/science/hdf/clearinghouse/irim/irim_hdf.html*

[4] Hacking, P.B. et al. 1997, in *Diffuse Infrared Radiation and the IRTS*, ed. H.Okuda, T.Matsumoto,& P.Hut. ASP Conference Series, in press.

[5] Kessler,M.F., et al. 1996 *Astr. Astrophys.* **315**, L27. This is the first paper in a special issue devoted to the results from *ISO*

[6] Moorwood, A.F.M., et al. 1996, *Astr. Astrophys.* **315**, L109

[7] Rigopoulou, D., et al. 1996, *Astr. Astrophys.* **315**, L125

[8] Rowan-Robinson, M., et al. 1997, **MNRAS**, in press

[9] Simmons, L., Fanson, J., Irace, W., Kwok, J., & Werner, M.W. 1996, *Proc.SPIE*, **2744**, 731

[10] Voit, G.M. 1992, *Astrophys. J.* **399**, 495

[11] Werner, M.W., and Eisenhardt, P.R.M. 1995, in *Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust*, ed. M.R.Haas, J.A.Davidson, & E.F.Erickson, ASP Conference Series **73**, 169