On the Space Infrared Telescope Facility and the Stratospheric Observatory for Infrared Astronomy: Letter Report

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Space Studies Board

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On April 21, 1994, Space Studies Board Chair Louis Lanzerotti sent the following letter to Dr. Wesley Huntress, associate administrator for NASA's Office of Space Science.

In your letter to Prof. Marc Davis, Chair of the Committee on Astronomy and Astrophysics (CAA), dated November 9, 1993, you requested that the National Research Council (NRC) conduct an assessment of scientific capability of the rescoped Space Infrared Telescope Facility (SIRTF) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) in the light of previous NRC recommendations for space and airborne astronomy. The CAA, a joint committee of the Space Studies Board and the Board on Physics and Astronomy, established a Task Group on SIRTF and SOFIA to perform this study. I am pleased to enclose the Task Group's report.

Please contact me if you have any questions about the report.

REPORT OF THE TASK GROUP ON THE SPACE INFRARED TELESCOPE FACILITY ANDTHE STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

I. INTRODUCTION

In the 1991 National Research Council report, *The Decade of Discovery in Astronomy and Astrophysics,* the Astronomy and Astrophysics Survey Committee characterized the 1990s as "the Decade of the Infrared." The Bahcall report (after the Committee Chair, John Bahcall) expected that the ongoing revolution in the technology for detecting infrared and submillimeter radiation would lead to major advances in our understanding of fundamental astronomical problems ranging from solar system studies to cosmology. To this end, the report (pp. 75-80) strongly recommended three new infrared equipment initiatives:

- The Space Infrared Telescope Facility (SIRTF)-a 0.9-m-diameter, liquid-helium-cooled telescope with unprecedented sensitivity for imaging and

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moderate-resolution spectroscopy between 2 and 700 μm, to be launched by a Titan IV-Centaur into a high Earth orbit (altitude 100,000 km);

- An 8-m-diameter telescope, optimized for low-background, diffraction-limited operation between 2 and 10 μm and equipped with adaptive optics, to be built on Mauna Kea, Hawaii; and
- The Stratospheric Observatory for Infrared Astronomy (SOFIA)-a 2.5-m-diameter telescope mounted in a Boeing 747 aircraft and optimized for diffraction-limited imaging and high-resolution spectroscopy from 30 μm to submillimeter wavelengths.

SIRTF and the 8-m ground-based telescope were the highest-priority large, new initiatives in, respectively, the space- and ground-based categories. SOFIA was one of the highest-rated moderate initiatives. The report stressed that the combination of these three instruments provided enormous potential for discovery in the large and relatively unexplored wavelength band between 1 and 1000 μm-an especially relevant spectral region for studies of cosmology, galaxy evolution, star-forming regions, and planetary systems.

Since the report's release in 1991, NASA's ability to undertake new missions, particularly large missions, has become increasingly constrained. The constraints have arisen not only from budget restrictions, but also from concerns about the risks associated with large, complex missions. NASA planners are now rescoping proposed initiatives to comply with new guidelines for the development of scientific missions. NASA's Associate Administrator for Space Science, Wesley T. Huntress, Jr., has requested that the Committee for Astronomy and Astrophysics (CAA) [1] assess the effects of proposed changes to the SIRTF and SOFIA programs on their respective abilities to achieve the scientific goals that justified their high rankings in the Bahcall report.

In response, the CAA established a task group with CAA members Doyal Harper (University of Chicago) as chair and Anneila Sargent (California Institute of Technology) as vice chair to review the current status of SIRTF and SOFIA. Members of the Task Group on SIRTF and SOFIA (TGSS) are listed in Appendix A [not provided]. Their charge was to "determine whether the rescoped Space Infrared Telescope Facility (SIRTF) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) missions remain responsive to the principal scientific objectives identified in the report The Decade of Discovery in Astronomy and Astrophysics (the Bahcall report) for infrared astronomy and [to] previous recommendations of the Space Studies Board's Committee on Space Astronomy and Astrophysics and earlier astronomy and astrophysics survey committee reports." The charge specified further that "[t]he TGSS's determination will be based on an evaluation of technical information about rescopings of these two major NASA programs."

The TGSS met at NASA's Ames Research Center on February 17 and 18, 1994, and heard presentations from representatives of both SIRTF and SOFIA. Project Scientists Michael Werner (JPL, SIRTF) and Edwin Erickson (NASA-Ames, SOFIA) described the status of their respective missions, including the scientific and technical rationale behind the redesign of the mission elements and expected costs. The scientific aims of SIRTF and SOFIA were amplified by science team members George Rieke (University of Arizona) and David Hollenbach (NASA-Ames), respectively; SOFIA Deputy Project Scientist Edward Dunham (NASA-Ames) addressed the particular capabilities of SOFIA for planetary science, while the Project Manager for SIRTF, Lawrence Simmons (JPL), elaborated on the details of its extensive technical redesign. The TGSS's assessment of the current state of the missions is based on these presentations.

The TGSS concludes that, despite reductions in scientific scope that have resulted from NASA's current cost ceiling for new science missions, SIRTF remains unparalleled in its potential for addressing the major questions of modern astrophysics highlighted in Chapter 2 of the Bahcall report. The TGSS is unanimous in its opinion that SIRTF still merits the high-priority ranking it received in the Bahcall report. The task group also concludes that the SOFIA scientific capabilities are unchanged from those that contributed to its high ranking among the moderate missions in the report. As a result, the TGSS discusses SIRTF more extensively than SOFIA. The task group notes, however, that SIRTF's redefinition renders the rationale for complementary SOFIA (and ground-based, IR-optimized 8-m) observations even more compelling. An account of the TGSS's deliberations follows.

II. SIRTF

1. Technical Status

The goal of the SIRTF redesign was to reduce the mission cost from the $1.3B (FY90; equivalent to $1.5B FY94) estimated for the version considered by the Bahcall committee to below NASA's guideline of $388M (FY94), exclusive of launch vehicle costs. All aspects of the mission have been profoundly affected by this major restructuring. The SIRTF team now focuses its scientific program on four areas identified in the Bahcall report as being of major importance in modern astrophysics. This scientific program exploits SIRTF's unique strengths and (along with corresponding cost-benefit trade-offs) has motivated and constrained the redesign of the mission elements as described below. Conceptually, the major aspects of the rescoped mission appear to be well understood, although they are as yet incomplete in detail. The current JPL estimate of the development cost for the project as described is $310M (FY94), which includes a $68M reserve, and is $78M less than the NASA guideline.

A. Orbit

A solar orbit rather than a high Earth orbit is now planned for the spacecraft. The advantages and feasibility of such an orbit have only recently been recognized. It allows greater launch vehicle flexibility, a substantially improved thermal environment, and enhanced sky coverage for observations. Spacecraft control and scheduling of observations will be simplified. The spacecraft will, however, move significantly farther from the Earth and reach ~ 0.3 AU after 2.5 yrs. Communications will require the use of NASA's Deep Space Network (DSN).

B. Spacecraft

The rescoped SIRTF incorporates a cryogenically cooled, 85-cm-diameter telescope with performance over the 3- to 180-µm range limited only by the natural background radiation. The estimated mass of the redefined spacecraft is only 1000 kg, which is less than that of the highly successful Infrared Astronomical Satellite (IRAS), launched in 1984, and only about half that of the Cosmic Background Explorer (COBE), launched in 1989. This very substantial reduction in mass results from modifications in virtually all areas. Liquid helium requirements are much lower because of the improved thermal environment in solar orbit, the significant improvements in telescope and instrument power dissipation, and a decrease in planned facility lifetime from 5 to 2.5 years. Moreover, the telescope will be launched warm, with a potential for cost savings not only in dewar design and fabrication but also in testing and integration. After launch, the telescope will first cool radiatively and, subsequently, via enthalpy of the gas escaping from the liquid helium dewar that cools the scientific instruments.

C. Launch Vehicle

Due to the significantly reduced spacecraft mass and the solar orbit, a much less expensive launch vehicle can be employed. The revised SIRTF will be able to use either an Atlas II or Delta 7925 vehicle, rather than requiring a Titan IV-Centaur.

D. Scientific Instruments

The redefined SIRTF scientific instrument payload incorporates 11 larger-format detector arrays (down from 19 in the previous concept). Three arrays use InSb detector material, three use Si:As IBC (impurity band conductor), and three use Si:Sb IBC; the remaining two use Ge:Ga and stressed lattice Ge:Ga (see Table 1). The number of cryogenic mechanisms has decreased from 23 to 1, leading to substantial reductions in power dissipation. The decreased complexity of the payload minimizes risk as well as cost. The lower number of observing modes combined with the increased pointing flexibility in the solar orbit should result in very high observing efficiency.

TABLE 1

SIRTF Capabilities: Current Concept

Wavelength	Detector Format	Detector Technology	Pixel Size	Field of View

3.5 μm	256 x 256	InSb	1.2”	5’ x 5’
4.5 μm	256 x 256	InSb	1.2”	5’ x 5’
8 μm	128 x 128	Si:As	2.4”	5’ x 5’
30 μm	128 x 128	Si:Sb	2.4”	5’ x 5’
70 μm	32 x 32	Ge:Ga	9.6”	5’ x 5’
160 μm	1 x 16	Ge:Ga (stressed)	19.2”	5’ x 20’

Spectroscopy

Wavelength Range	Resolving Power	Detector (array sizes as listed above)
4 – 5.3 μm	100	InSb
5 – 15 μm	100	Si:As
15 – 40 μm	100	Si:Sb
12 – 24 μm	600	Si:As
20 – 40 μm	600	Si:Sb
55 - 100μ	20	Ge:Ga

TABLE 2

Parameter	Titan Version (Bahcall Report)	Current
Wavelength range	2 – 700 μm	3 – 180 μm
Lifetime	5 yrs	2.5 yrs

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Aperture	92 cm	85 cm
Pointing stability	0.15 arcsec	0.25 arcsec
Secondary mirro position	6 degrees of freedom	Focus only
Diffraction-limited	>3 μm (0.9” @ 3 μm)	>6.5 μm (2” @ 6.5 μm)
Planetary tracking	High-speed,	Stepwise
Average data rate	120 kbps	40 kbps
Mode	Full observatory	Key project

Important Simplifications

Parameter	Titan Version (Bahcall Report)	Current Concept
Cooled instrument volume	0.8 m^3	0.2 m^3
Cryogenic mechanisms	23	1
Number of detector arrays	19	11
Cryogenic instrument mass	200 kg	50 kg
Cryogenic instrument heat dissipation	17mW	10mW
Warm electronics (mass/volume/power)	97 kg/0.5 m^3/150W	75 kg/0.08 m^3/75W
Fine guidance	Internal	External

The simplification has been achieved through significant reduction in capabilities. Diffraction-limited imaging in the 3-μm region, polarimetry, 2.5- to 4-μm spectroscopy, and high-resolution spectroscopy in the 4- to 13-μm range and longward of 40 μm are no longer possible. In addition, there will be no bolometers for imaging longward of 200 μm. Since the filter wheels associated with the imagers have been eliminated, narrow-band imaging will be less efficient, though still viable (by spatial scanning perpendicular to the slits in the spectrographic modes). The technical changes in the currently envisaged SIRTF mission are compared (Table 2) to the earlier version considered by the Bahcall report.

However, there have been significant gains in performance in other areas. Detector technology has matured considerably since the time of the Bahcall report, particularly in the key 27- to 40-μm region. Here, high-quantum-efficiency, low-noise, 128 x 128 Si:Sb IBC arrays have replaced lower-efficiency 16 x 16 extrinsic Ge arrays. At other wavelengths, combinations of array size and performance that were only predicted in 1990 have now been realized in the laboratory. The detector performance is now such that SIRTF observations will be limited only by the fundamental photon noise of the extraterrestrial sky brightness (principally thermal emission from zodiacal dust from our vantage point within the inner solar system), not only for broad-band imaging around 3.5, 4.5, 8, 30, 70, and 160 μm, but also for spectroscopy in the bands from 4 to 40 μm, 13 to 40 μm, and 55 to 100 μm with spectral resolving power of 100, 600, and 20, respectively. Table 3 summarizes the capabilities that have been lost in the new SIRTF concept as well as the gains.

TABLE 3

Changes in SIRTF Capabilities

Improved SIRTF Capabilities	Deleted SIRTF Capabilities
Availability of Si:Sb arrays-improved quantum efficiency, larger format in the 20- to40-μm range Greater reliability through simplified hardware Solar orbit instead of high Earth orbit results in: a. greater observing efficiency-shorter life b. better sky access-improved response to targets of opportunity c. a more stable thermal environment-simpler attitude control	

Deleted SIRTF Capabilities

Imaging

Narrow-band imaging (filter wheels)

Sub-millimeter imaging (180 – 700 μmm)

Short-wavelength imaging (2 – 3 μm)

High-resolution imaging (2 – 5.5 μm)

Polarimetry

Spectroscopy

Long-wavelength spectroscopy (40 - 200 μ

Short-wavelength spectroscopy (2.5 – 4 μm)

High-resolution spectroscopy (4 – 13 μm)

E. Ground Operations

The solar orbit simplifies ground operations and, with the streamlined instrumentation concept, will provide very high observing efficiency, possibly around 75%, but will require support of the DSN. However, the reduced data rate and shorter lifetime demand careful approaches to planning and executing the science program in order to maximize scientific productivity while assuring community involvement. The traditional "observatory" paradigm originally envisaged for SIRTF, in which scientific programs evolve as a wide spectrum of users learn and test the capabilities of the system, is no longer applicable. The SIRTF team now favors an approach whereby much of the observing time is devoted to large-scale projects (Key Projects) that will include large imaging and spectroscopic surveys. In order to ensure optimum scientific returns, the broader astronomical community will be actively encouraged to participate in the definition of these Key Projects well before launch. To enable follow-up activities by the community during the shorter lifetime, Key Project data will be nonproprietary. Very early release of processed and calibrated data products is planned. Such programmatic changes should help counteract the loss of science output due to the shorter mission, particularly in view of the increased coverage of the sky afforded by the solar orbit.

2. Scientific Capabilities

The SIRTF redefinition and operations are driven by four scientific programs: (1) preplanetary and planetary debris disks, (2) brown dwarfs and superplanets, (3) ultraluminous galaxies and active galactic nuclei, and (4) deep surveys of the early universe. By focusing on these important areas in which SIRTF observations can make unique contributions, the SIRTF team has greatly simplified the instrument design and operating modes and has vastly reduced mission costs. The four programs provide a sharp scientific focus that is entirely consistent with the high-priority objectives identified in the Bahcall report. Scientific research conducted since the report's publication has served only to emphasize that these programs encompass some of the most compelling problems in modern astronomy. In addition, as a consequence of the unprecedented sensitivity across the whole 3- to 180-μm band, SIRTF will have strong capabilities for addressing a wide range of other astronomical problems.

Due largely to its advanced detector arrays, the redefined SIRTF retains much of its original scientific capability and preserves its major advantage over other instruments-unprecedented sensitivity in the large, relatively unexplored, and astrophysically important region of the spectrum between 3 and 180 μm. Again, the TGSS stresses that the sensitivity is now limited only by the natural extraterrestrial sky brightness. Moreover, the large-format arrays allow full sampling of the diffraction disk beyond 6 μm, a capability that is essential for minimizing the effects of source confusion in very deep integrations.

The powerful focal-plane arrays have a profound impact on all of the science programs. Photometric and spectroscopic surveys will substantially extend the range of preplanetary and disk characteristics known from IRAS. Imaging programs that can reach much fainter systems will strongly constrain disk models. Targeted searches of nearby stars and young clusters for brown dwarf candidates and surveys for planetesimals in the Kuiper Belt will be facilitated. Studies of active galaxies and the early universe will benefit enormously from the high signal-to-noise ratio and dense spatial sampling that, coupled with sophisticated extraction techniques, will enable deep searches at unprecedented sensitivity. Observations of ultraluminous galaxies out to redshifts of z ~ 10 will be possible. Measurements of the contribution from faint galaxies will be an important complement to COBE measurements of the cosmic background. The TGSS notes that SIRTF's greatest asset is likely to be its potential for discovery. Like IRAS, the task group expects it to open new areas that will then be studied at other wavelengths and at higher spatial and spectral resolution with the upcoming generation of large ground-based telescopes such as Keck, Gemini, and the European Southern Observatory's Very Large Telescope, with airborne instruments like SOFIA, and with future space-based or lunar telescopes.

Although the redesign of SIRTF has been guided predominantly by the needs of the four programs described above, the new instrument will make major contributions in other astronomical areas. Nevertheless, there has been some unavoidable loss of scientific opportunity. The restricted technical capabilities will preclude a number of the programs originally proposed. Eliminating the submillimeter bolometer system will prevent cosmological observations involving the Sunyaev-Zel'dovich effect and the cosmic background anisotropy. Without the far-infrared spectroscopic capability, studies of important cooling lines in the interstellar medium of our own and other galaxies will not be possible. In addition, a number of goals of the planetary program are now unattainable. In particular, investigations of planetary atmospheres that rely strongly on imaging in the near infrared and on high-resolution spectroscopy between 4 and 13 μm cannot be carried out.

In deep searches for distant galaxies, for example, SIRTF will provide orders-of-magnitude improvement over ISO. Figure 1 is a comparison of the relative astronomical capabilities of the rescoped SIRTF and ISO and, when compared with Figure 4.2 in the Bahcall report, highlights the dramatic improvement in SIRTF's detection capability since the time of that report's release. The relative astronomical capability is a figure of merit combining point-source sensitivity, array size, facility lifetime, and efficiency in the following relation:

$$\text{Relative astronomical capability} = \frac{\text{(facility lifetime)} \times \text{(number of array pixels)} \times \text{efficiency}}{\text{(limiting flux density)}^2}$$

Roughly speaking, this expression gives the number of resolution elements on the sky that can be measured to a given flux level by a facility during its lifetime (see p. 78 of the Bahcall report). Depending on wavelength, the relative astronomical capability of SIRTF will exceed that of ISO by factors of 103 to 108.

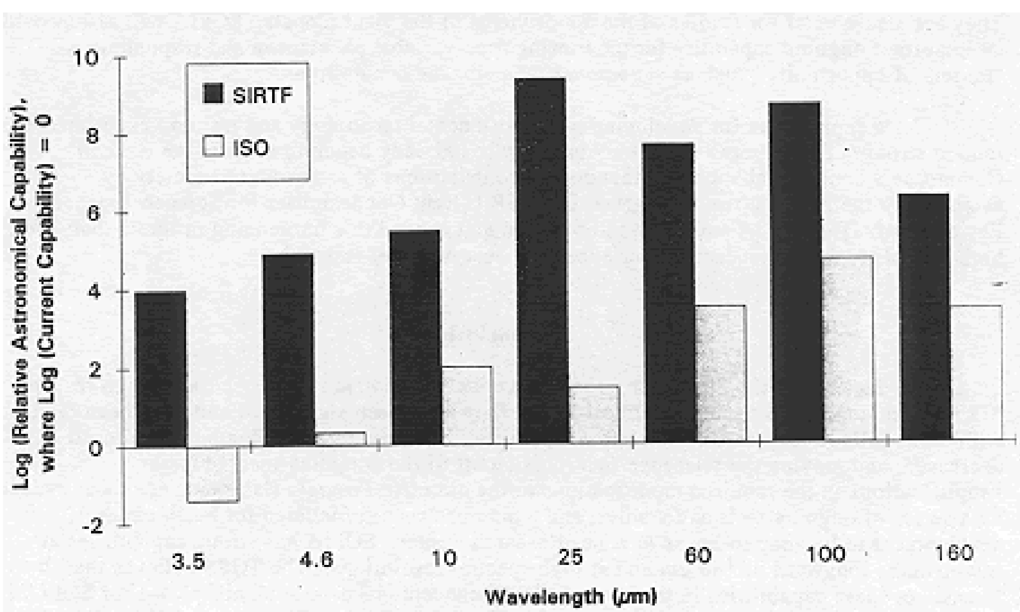

FIGURE 1 Relative astronomical capability of SIRTF and ISO.

3. Conclusions

The TGSS fully endorses the Bahcall Committee's ranking of SIRTF. The proposed rescoped mission remains responsive to the principal scientific objectives of the Bahcall report. In terms of cost, SIRTF has moved into the moderate mission category while retaining much of its scientific capability. The mission has also been much simplified, significantly reducing risk factors. The revised observing program has been tailored to focus on a few well-defined, high-priority objectives that include some of the most important problems in modern astrophysics, but the instrument remains a powerful tool for a variety of other studies. Despite drastic rescoping, SIRTF has maintained an exceptionally high level of scientific potential, largely as a result of dramatic technological advances in the area of infrared detector arrays. The interaction of university-based scientists and U.S. industry in this endeavor has been remarkably successful; the sensitivity of SIRTF observations is now limited only by background photon noise. The TGSS believes that it is imperative that NASA and the astronomy community capitalize on this investment. It appears to the TGSS that the proposed Key Projects program is an excellent way of involving the whole astronomical community in SIRTF. This program and other mechanisms for promoting and coordinating participation by a broad user community are essential for maximizing scientific returns from a shorter mission.

III. SOFIA

1. Technical Status

The current estimate of the cost of SOFIA program development to NASA's Astrophysics Division is $178M (FY94), including vehicle procurement, airframe modification and refurbishment, ground support systems, systems integration and testing, and a $42M reserve. For comparison, the corresponding cost projected in the Bahcall report was $230M (FY90; equivalent to $276M FY94). Neither figure includes the cost of the telescope itself since foreign participation was already assumed at the time of the Bahcall report. Participation in SOFIA is a high priority for the German space agency, DARA, which anticipates supplying the telescope system and ongoing operational support in return for access to approximately 20% of the science flights.

A major portion of the cost reduction has been realized through a redesign in which the telescope system was shifted from a location forward of the wing (the scheme employed in the currently operating Kuiper Airborne Observatory, KAO) to a position between the wing and tail section, allowing important simplifications in the required aircraft modifications. An aft location requires construction of only one new pressure bulkhead, rather than two, and far fewer of the aircraft control systems have to be rerouted around the telescope cavity door. Since the time of the Bahcall report, there has also been a significant decline in the price of used Boeing 747 aircraft.

A series of engineering studies covering a broad range of factors, including aerodynamics, aircraft structural analysis, aero-optics, and telescope design, have reduced uncertainties in the revised concept. Important issues in moving the telescope to the aircraft tail were the effect of the thicker boundary layer on image quality and the magnitude of scattered infrared radiation from the jet engines and hot exhaust gases. These questions have been addressed with both theoretical simulations and in-flight tests. The KAO was used for measurements of seeing and to test a passive boundary-layer control system. Airflow around the telescope cavity has been studied using computational fluid dynamics and wind-tunnel tests on a scale model of a Boeing 747. In-flight vibration tests and measurements of infrared emission from jet engines and exhausts were made using actual 747 aircraft. An aft-mounted telescope appears to meet all of the performance specifications and scientific objectives envisioned for SOFIA at the time of the Bahcall report.

The SOFIA project team has identified several additional studies that are needed prior to final selection of the model of 747 aircraft and its procurement (in particular, further wind-tunnel tests of aft-mounted cavity configurations), but overall the program seems well considered and ready to proceed to Phase C/D development. Ames Research Center now plans to undertake a larger fraction of the SOFIA development in-house. This should minimize programmatic risks by building on the unique expertise of Ames personnel in aerodynamics (especially in the area of boundary-layer control) and in operating science platforms on aircraft.

2. Scientific Capabilities

The Bahcall report emphasized the value of SOFIA for opening up to routine observations the wavelength range from 30 to 350 mm, for training new generations of experimentalists, and for developing and testing new instruments. It also stressed that SOFIA's capability for diffraction-limited imaging and high-resolution spectroscopy at wavelengths inaccessible from the ground would complement SIRTF's great sensitivity.

The report's conclusions regarding SOFIA are rendered more compelling with the elimination of SIRTF's very long wavelength, high spectral resolution, and polarimetric capabilities, and the reduction in its operational lifetime. The angular resolution afforded by SOFIA's large aperture (~ 2.5 m) and the possibility of achieving high spectral resolutions, with corresponding velocity resolutions of up to 1 km s-1, are of particular importance. Both capabilities will enhance dynamical studies of the high-density, moderate-temperature cloud cores where stars form, of the primitive nebulae around newly formed stars, and of the nuclei of infrared-luminous galaxies. They are also crucial for studies of the atmospheres of the giant planets. SOFIA will also provide an important ongoing capability for monitoring time-variable phenomena and responding to "targets of opportunity" such as supernovae, comets, and occultations.

SOFIA's capabilities for developing new instrumental technology and training experimentalists remain strong. The airborne astronomy program has already begun to address the Bahcall Committee's concerns about strengthening the contributions of astronomy to society by establishing the KAO outreach program, FOSTER (Flight Opportunities for Science Teacher Enrichment). The SOFIA team plans to build on and expand this burgeoning program that offers high school teachers first-hand experience with observational research.

3. Conclusions

Cost reductions in the SOFIA program have been less radical than those required to rescope SIRTF from a major to a moderate mission, but they have been significant and have been realized with essentially no decrease in scientific capability. The price of used Boeing 747 aircraft has decreased, and moving the telescope to a location aft of the wing has enabled major simplifications in the required modifications to the aircraft. Program risks have also been reduced by a series of ongoing tests and studies, and a plan has been formulated for much of the development to be done in-house at Ames Research Center. SOFIA has strong capabilities at wavelengths longward of 180 μm and at high spectral resolutions. The TGSS believes that the absence of these capabilities in the current SIRTF concept makes the scientific case for SOFIA more compelling. The TGSS concludes that SOFIA, with frequent flight opportunities for a broad range of state-of-the-art instrumentation programs, remains a uniquely powerful facility for science and continues the airborne program's role of developing technology for future space missions, for training experimentalists, and for educational outreach, as envisaged in the Bahcall report.

1 The CAA is a joint activity of the National Research Council's Space Studies Board and the Board on Physics and Astronomy.