## NRA-03-OSS-01-VM
## Call for Mission Concepts: Space Science Vision Missions

# Science Promise and Conceptual Mission Design Study for SAFIR – the Single Aperture Far Infrared Observatory

SAFIR is a large (10m-class), cold (4-10K) space telescope for wavelengths between 20$\mu$m and 1mm. It will provide sensitivity of a factor of a hundred or more over that of SIRTF and Herschel, leveraging their capabilities and building on their scientific legacies. Covering this scientifically critical wavelength regime, it will complement the expected wavelength performance of the future flagship endeavors JWST and ALMA. This vision mission will probe the origin of stars and galaxies in the early universe, and explore the formation of solar systems around nearby young stars. Endorsed as a priority by the Decadal Study and successive OSS roadmaps, SAFIR represents a huge science need that is matched by promising and innovative technologies that will allow us to satisfy it. In exercising those technologies it will create the path for future infrared missions. This study will refine the scientific goals of the mission, explore promising approaches for it's architecture, and sharpen understanding about remaining technological challenges that will allow us to recommend optimal strategic investments. Our broadly based team will show how SAFIR responds to the scientific challenges in the OSS Strategic Plan, and how the observatory can be brought within technological reach.

Principal Investigator: Dan Lester U Texas

CoI-Investigators

| | | |
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| Gordon Stacey, Cornell | Dominic Benford, GSFC | Charles Lawrence, JPL |
| Erick Young, U Arizona | David Leisawitz , GSFC | Bill Langer, JPL |
| Andrew Blain, Caltech | Harvey Moseley, GSFC | Mark Dragovan, JPL |
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| Eri Cohen, JPL | Jennifer Dooley, JPL | John Hong, JPL |
| Matt Greenhouse, GSFC | Matt Griffin, Cardiff | John Grunsfeld, JSC |
| Bob Menzies, JPL | Phil Stahl, MSFC | Brenda Ward, JSC |

Industry Partners:

| | |
|---|---|
| Ball Aerospace Corp. | Lockheed Martin Corp. |
| Boeing Corp. | Northrop Grumman Corp. |

# PROPOSAL COVER PAGE

(Date : Sep 03 2003)

**VM03-0023-0014**

**Name of Submitting Institution:** University of Texas at Austin **Congressional District:** 10

**Certification of Compliance with Applicable Executive Orders and U.S. Code**

By submitting the proposal identified in this Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing institution (or the individual proposer if there is no proposing institution) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications contained in this NRA [namely, (i) Assurance of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, and (ii) Certifications, Disclosures, And Assurances Regarding Lobbying and Debarment & Suspension]. Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

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**[1] ... PI Information**

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**[3] ... Proposal Title (Short and/or Full)**

| | |
|---|---|
| **Short Title:** | SAFIR: the Single Aperture Far IR Observatory |
| **Full Title:** | Science Promise and Conceptual Mission Design Study for SAFIR - the Single Aperture Far Infrared Observatory |

**[4] ... Proposed Start/End Date**

| | |
|---|---|
| **Start Date:** | 04/01/2004 |
| **End Date:** | 03/31/2005 |

**[5] ... Themes**

(1) Astronomical Search for Origins & Planetary Sys
(2) Structure and Evolution of the Universe

**[6] ... Predecessor Information**

| | |
|---|---|
| **Predecessor Information:** | None |

**[7] ... Summary**

SAFIR is a large (10m-class), cold (4-10K) space telescope for wavelengths between approximately 20microns and 1mm. It will provide sensitivity of a factor of a hundred or more over that of SIRTF and Herschel, leveraging their capabilities and building on their scientific legacies. Covering this scientifically critical wavelength regime, it will complement the expected wavelength performance of the future flagship endeavors JWST and ALMA. This vision mission will probe the origin of stars and galaxies in the early universe, and explore the formation of solar systems around nearby young stars. Endorsed as a priority by the Decadal Study and successive OSS roadmaps, SAFIR represents a huge science need that is matched by promising and innovative technologies that will allow us to satisfy it. In exercising those technologies it will create the path for future infrared missions. This study will refine the scientific goals of the mission, explore promising approaches for it's architecture, and sharpen understanding about remaining technological challenges that will allow us to recommend optimal strategic investments. Our broadly based team will show how SAFIR responds to the scientific challenges in the OSS Strategic Plan, and how the observatory can be brought within technological reach.

**[8] ... Cage Code, Duns, TIN**

| | |
|---|---|
| **Cage Code:** | 9B981 |
| **DUNS Number:** | 170230239 |
| **TIN Number:** | 746000203 |

**[9] ... Carrier**

| | |
|---|---|
| **Is this an investigation on sounding rocket, a balloon, or an airplane? :** | No |

**[10] ... Institution Type**

| | |
|---|---|
| **Institution Type:** | Educational institution |

**[11] ... Research Category**

| | |
|---|---|
| **Research Category:** | Instrument and Mission Development |

**[12] ... International Proposal**

| | |
|---|---|
| **International Participation & Description:** | No |

**[13] ... US Government Agency Participation**

| | |
|---|---|
| **U.S. Government Agency Participation:** | Yes (John Mather CoI NASA GSFC $0 Dominic Benford CoI NASA GSFC $10K David Leisawitz CoI NASA GSFC $10K Samuel Moseley CoI NASA GSFC $10K Harold Yorke CoI NASA JPL $10K Charles Lawrence CoI NASA JPL $10K William Langer CoI NASA JPL $10K Mark Dragovan CoI NASA JPL $10K Eri Cohen col NASA JPL $0 Jennifer Dooley col NASA JPL $0 John Hong col NASA JPL $0 Matt Greenhouse col NASA GSFC $0 John Grunsfeld col NASA JSC $0 Bob Menzies col NASA JPL $0 Phil Stahl col NASA MSFC $0 Brenda Ward col NASA JSC $0 ) |

**[14] ... Program**

| | |
|---|---|
| **Program Selection:** | Study Case 09: Far-Infrared Telescope |

**[15] ... Data1**

| | |
|---|---|
| **Use of Astronauts:** | Yes |

**[16] ... Data2**

| | |
|---|---|
| **Use of Nuclear Power:** | No |

**[17] ... Budget**

| Type | Year 1 | Total |
|---|---|---|
| **Direct Labor** | $24,000.00 | $24,000.00 |
| **Other Direct Costs** - Subcontracts | $0.00 | $0.00 |
| Other Direct Costs - Consultants | $0.00 | $0.00 |
| Other Direct Costs - Equipment | $0.00 | $0.00 |
| Other Direct Costs - Supplies | $0.00 | $0.00 |
| Other Direct Costs - Travel | $40,000.00 | $40,000.00 |
| Other Direct Costs - Other | $0.00 | $0.00 |
| **Indirect Costs** | $32,000.00 | $32,000.00 |
| **Other Applicable Costs** | $229,000.00 | $229,000.00 |
| **Subtotal** - Estimated Costs: | $325,000.00 | $325,000.00 |
| **Less:Proposed Cost Sharing** - Cost Sharing: | $0.00 | $0.00 |
| **Budget Total** | **$325,000.00** | **$325,000.00** |

# Table of Contents

# Scientific/Technical/Management

## Section 1. Study Objectives and Significance

### 1.1 Study Basis

In response to the Call for Vision Mission Studies - Study Case 9 – a “Far Infrared Telescope”, our team submits this proposal for the SAFIR (Single Aperture Far InfraRed) mission – a large collecting area, cold, far-IR and submillimeter telescope. SAFIR is a prime Office of Space Science example of fundamental scientific need coupled with emerging technological feasibility.

*The “Decadal Report – Astronomy and Astrophysics in the New Millennium”, recommended a program for infrared astronomy that “would build on the experience gained with NGST to construct [a JWST-scale filled-aperture far-IR telescope] SAFIR, and ... in the decade 2010 to 2020, build on the SAFIR, TPF, and SIM experience to assemble a space-based, far-infrared interferometer.” In responding to this NRA, the far-infrared / submillimeter community follows this dual thrust by submitting complementary proposals for Study Cases 9 and 12. The large aperture telescope – SAFIR –- will have unprecedented sensitivity for studying stars and galaxies formed when the Universe was less than a billion years old and the subsequent evolution of these systems over the aeons. SAFIR alone, however, will not tell the full story. At these long wavelengths most sources identified by SAFIR may be unresolved spatially. SPECS, a long baseline far-infrared interferometer with more challenging technical requirements, will be required to clearly exhibit structure in these sources, and to more completely define evolutionary processes. These two missions share not only scientific synergy, but also a host of technical challenges. If NASA selects both Study Cases 9 and 12 for further investigation, the teams will initiate a cost-effective exchange of information.*

SAFIR embraces concepts known as DART and FAIR, which have appeared in earlier OSS roadmaps. With major science goals that span four enterprise objectives in the Origins and SEU themes, and offering contributions to SSE, this mission offers clear scientific traceability and relevance to overarching NASA Vision, Mission, and Strategic goals. In the call for SAFIR by the NAS Decadal Study, in the white paper Community Plan drafted by the far-IR and submillimeter community, and through endorsement by the SScAC, enterprise objectives that SAFIR addresses represent the consensus need of the space science community. This reflects true partnership of agency and community. The four enterprise objectives are:

- understanding how today’s Universe of galaxies, stars and planets came to be
- understanding development of structure and cycles of matter and energy in the Universe
- learning how the solar system originated and evolved to its current diverse state
- learning how stars and planetary systems form and evolve

We also recognize SAFIR’s potential for educational objectives, embracing agency goals of inspiring and motivating students, and engaging the public in shared exploration and discovery.

The main criterion of scientific merit for OSS program planning is met by the consensus noted above. Technology requirements for likely implementations of SAFIR are based on previous and queued IR missions such as IRAS, ISO, SIRTF, SOFIA and JWST, as well as Astro-F, Herschel, and SPICA. Technology developed for SAFIR will, in turn, enable even more capable IR telescopes. Thus feed-forward in science discovery and technology are hallmarks of the mission. The synergy noted above between a near-term SAFIR and a more challenging longer-term SPECS is consistent with the enterprise strategic principle of combining complementary missions into mission lines. Since funding for the proposed study is limited we focus our plan on discrete objectives in order to provide clear and complete products. These objectives include

• Development of science rationale for SAFIR in response to SIRTF results, and consistent with goals of other observatories, including SOFIA, Herschel, JWST and ALMA. This will constitute a SAFIR Science Summary document, and a strawman Design Reference Mission document.

• A clear understanding of SAFIR science trades involving telescope size, temperature, spectral range, resolution, and specific engineering requirements. The resulting SAFIR Concept Review document will give NASA tools to make well informed choices about implementation.

• Development of low-level concepts for architecture and implementation that are needs-compliant. A SAFIR Technology Roadmap will be developed for such investment planning.
• An examination of the pros and cons of astronaut deployment, integration and test of SAFIR, consistent with recent strategic efforts (e.g. NEXT) will be included in the Concept Review.

A supplemental objective is the engagement of the community, harnessing their insights into the challenges that we face. This objective will be met by regular reports to the community. Understanding that the broad scientific value of SAFIR has already been strongly endorsed by the community we will, in this proposal, only briefly review those goals. We devote available space to our plans for refining these science goals, flowdown into requirements, and methodology for handling key technical issues.

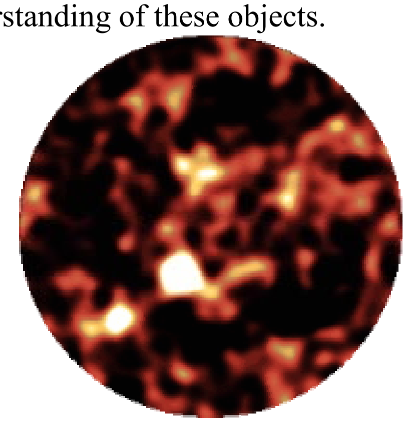
**1.2 Science Goals and Significance of SAFIR**

We review below several primary science goals of SAFIR in order to illustrate the breadth and depth of the mission science. Our study will flesh out these and other science goals, which will constitute our SAFIR Science Summary. For each goal, targeted Origins "Research Areas" and SEU "Research Focus Areas" (as numbered in 2003 roadmaps) are identified. *These illustrate alignment to the specifics of the OSS 2003 Strategic Plan.*

**Making Primordial Stars:** (Origins 1, 3, 4; SEU 8, 9) Among WMAP's most exciting results is the measurement of an optical depth, and the inference of star formation at z~20.. Reionization of the primordial gas by UV photons from these very first stars is a huge milestone in cosmic evolution, often called the "end of the dark ages". These first stars make the first heavy elements (C, N, O, Fe, etc) – "metals" – which profoundly influence subsequent star, galaxy, and planet formation. Probing reionization will be a key program for future astrophysics missions. Important spectral lines from the formation of the very first (H, He) stars are emitted at restframe near and mid-IR wavelengths and will be observed in the mid-IR to submillimeter, where SAFIR's huge sensitivity offers excellent discovery potential. A major thrust of our Science Summary will be to assess the role SAFIR could play in studying the evolution of primordial stars. We will compile literature and engage theorists to generate a scenario for this process.

Our first look reveals a variety of published results: (1) As the stars form, collapsing clouds are cooled primarily by molecular hydrogen transitions at 8-30μm rest wavelength. Redshifted, such lines are in the far-IR and submillimeter. During collapse, a single such protostar can radiate 10-100$L_o$ in each of the handful of these rotational $H_2$ lines. It is estimated that a large ($10^{11}$ $M_o$) protogalaxy could harbor as many as $10^4$ such protostars at a given time over its $10^7$ yr dynamical lifetime. Such a collection could be detectable by SAFIR. (2) The supernova explosion from an initial massive star could produce overdense shocks in the ISM and reform $H_2$, which can then radiate as much as 10% of the ~$10^{53}$ ergs released. Such an object would outshine the rest of the host galaxy and be detectable with SAFIR. We will identify specific tests of these scenarios that SAFIR could address. As the study proceeds, we will consider trades on SAFIR's capabilities (sensitivity, spectral resolution), in testing our understanding of these objects.

**When the Universe Made Galaxies:** (Origins 1, 3, SEU 8, 9) It is now understood that the far-IR and submillimeter sky is littered with cosmological sources. The powerful infrared background is dominated by sources unresolved by existing missions. These sources generally have very faint optical counterparts, and are thought to be heavily obscured young galaxies near the epoch of most intense star and galaxy formation. We know little about these except that they are blue in the submillimeter, with redshifted luminosity output that peaks at several hundred microns. SAFIR will observe these galaxies at their spectral peaks, and measure their spectroscopic redshifts, luminosities, physical conditions and star formation rates. JWST should detect these first galaxies, but SAFIR will tell us why they hide. In this way, SAFIR will trace back star formation in the universe in an unbiased way past the peak of galaxy formation to z>~5. We will consider SAFIR sensitivity goals on the basis of model stellar populations at this redshift, taking into account the

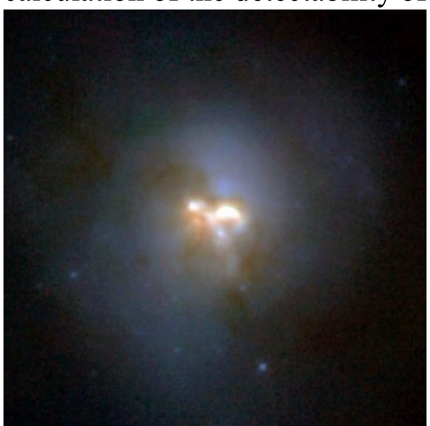


The submillimeter galaxies in this 3' HDF JCMT map will be dramatically brighter in the far-IR. SAFIR will map them easily, and analyze them spectroscopically.

latest understanding of source luminosity functions and K-corrections from SIRTF.

**Seeing into the Heart of Galaxies:**: (Origins 4, 5, 6, 7; SEU 9, 10) On average in the local universe, roughly half of the energy emerges at far-IR wavelengths. This is because the primary luminosity sources in galaxies are often obscured by dust. The far-IR is not susceptible to extinction, and a key thrust for SAFIR will be to directly observe the obscured regions of star formation and nuclear accretion. Infrared spectroscopy offers excellent tools for measuring gas mass, density, and temperature as well as ionizing radiation hardness. Two fundamental questions can be addressed.

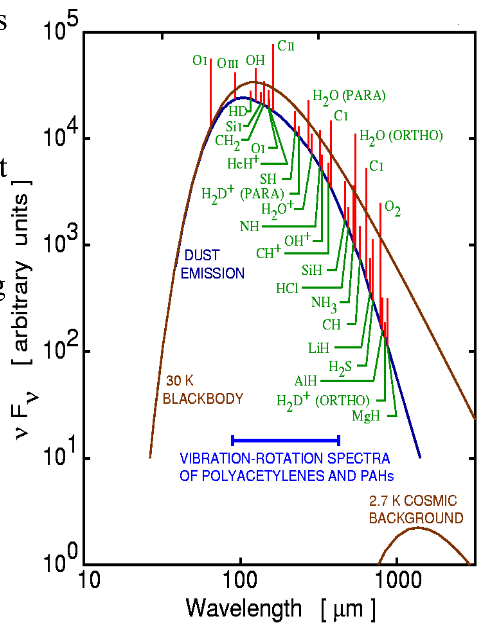
One is the energy source in Ultraluminous IR Galaxies (ULIGs). Are these astonishingly IR-bright (>$10^{12}L_o$) galaxies powered by accretion onto massive nuclear black holes, by superstarbursts, or by a combination of the two? Far-IR fine-structure lines that probe UV radiation hardness will provide answers to this. Diffraction-limited with a large aperture, SAFIR will resolve local ULIGs at their spectral peaks. Initial estimates suggest that SAFIR will be able to observe ULIGs out to z~10, well before the peak in their star formation activity, As part of our study, we will incorporate the results from the first SIRTF observations of ULIGs with recent cosmological measurements and predictions of SAFIR's sensitivity to make a detailed calculation of the detectability of the ultraluminous galaxies back to reionization.


Arp220 – a well known ULIG

Current theories hold that these two types of Seyfert galaxies, Seyfert Is and IIs, are the same type of object – a central accretion engine surrounded by a dense torus of molecular gas. Is this the result of a different viewing geometry – Seyfert IIs being viewed through the torus, and Seyfert Is being viewed unobscured along the axis of the torus? SAFIR can test this second question in two ways: 1) Spectroscopy of far-IR fine structure lines from the ionized medium – if present they will be observable regardless of the torus angle, and 2) Detection of the molecular torus itself in the far-IR rotational transitions of CO, OH, $H_2O$. We will quantify SAFIR's capabilities here, with particular attention paid to the complementary data that will be provided by SIRTF, Herschel, and ALMA.

**SAFIR and the Formation of Stars and Planets:** (Origins 6, 7, 8, 9, 10) Except at the earliest epochs, dust plays a prominent role in the formation of stars and planets. It is a principal player in the thermal evolution and structure of the dense molecular clumps from which they form. During early phases of collapse, dust obscures the emission at short wavelengths, but allows the thermal energy generated during compression to be radiated away, enabling continued contraction. Grain surfaces act as a chemical catalyst for the production of complex molecules, including organics, both prior to and during the star formation process. The result of chemical processing in star forming regions is a richness of molecular species. By studying line shapes, intensities, and excitation, information on the conditions can be extracted because many ions and molecules do not co-exist but rather trace regions with differing conditions.

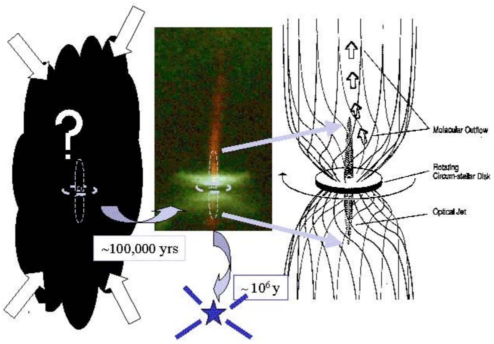
Finally, this dust is the raw material for building up planetesimals and comets, from clouds to protostars, Kuiper Belt Objects (KBOs), and ultimately, planets. How do cloud cores collapse? How does subfragmentation occur, which results in binary and multiple stellar systems?



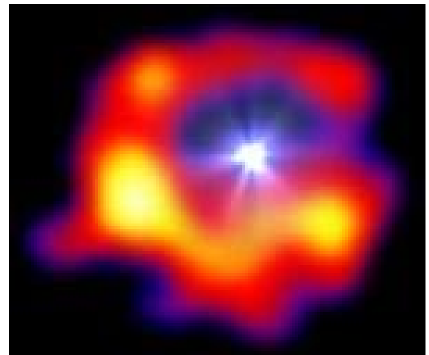
Spectral richness of gas in the far-IR – bright diagnostic lines for SAFIR.

What are the conditions within protostellar disks? When, where, and how frequently do they form planets?

Our study will evaluate how SAFIR can harness gaseous and solid state spectral tracers. We will do this through literature surveys and spectral modeling. We will consider the potential of SAFIR for direct measurements of Kuiper Belts surrounding nearby stars and. In particular, we will review the mission requirements to resolve and analyze recently discovered quasi-resonant submillimeter structure in fossil disk remnants that point to planet formation.




From collapsing cloud to solar system ...

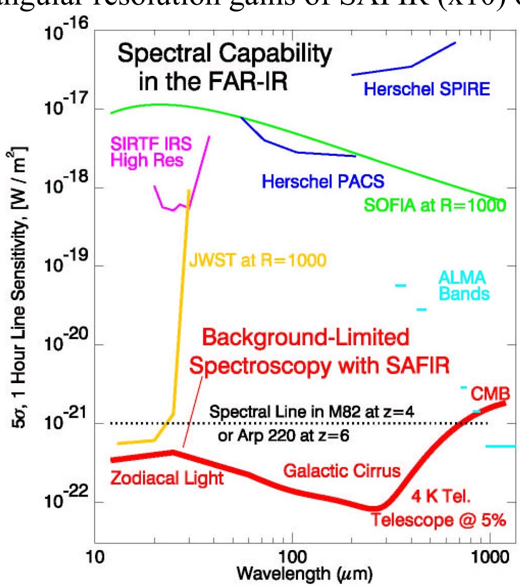


... SAFIR will resolve dusty fossil disks they leave behind around nearby stars.

### 1.3 Uniqueness of SAFIR

The unique contributions to be made by SAFIR were captured by the McKee-Taylor Decadal Survey: "The SAFIR Observatory will …study the relatively unexplored region of the spectrum between 30 and 300µm. It will enable the study of galaxy formation and the earliest stage of star formation by revealing regions too enshrouded by dust to be studied by NGST, and too warm to be studied effectively with ALMA." We expand on this, emphasizing investigations critical to the OSS Strategic Plan, and how SAFIR contrasts with other missions in this time frame.

• Since COBE, we know that galaxies generate much of their output in the far-IR. The mid-IR output is dominated by dust heated by young hot stars, so understanding star formation in the main era of galaxy assembly, z = 1-5, requires study at 30-600µm. Sensitivity (x100-1000) and angular resolution gains of SAFIR (x10) over SIRTF and Herschel are essential here.




Background-limited, R=1000 at wavelengths ~30-300µm, a 10m 4K SAFIR fills a chasm of sensitivity space between JWST and ALMA.

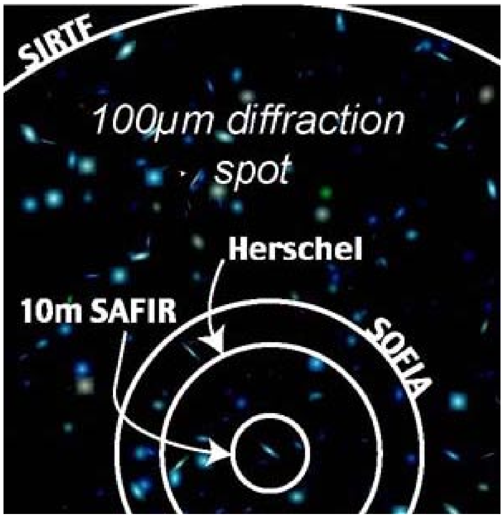
• Far IR fine structure lines (OI, NII, CI, CII, OIII) are among the main coolants of the ISM and can radiate ~1% of the luminosity of a star forming galaxy. Study of these lines with SAFIR gives new opportunity to watch the buildup of metals at all epochs, which is impossible from the ground. Limited resolution and sensitivity on Herschel and SOFIA prevents such study with those missions, and the wavelength range of SIRTF is inadequate for many of these lines.

• The low lying $H_2$ lines at rest wavelengths 17 and 28.2µm can reveal pristine gas near pop III stars in the early Universe. Sensitivity and resolution gains over SIRTF, SOFIA, and Herschel are critical, and it cannot be done from the ground.

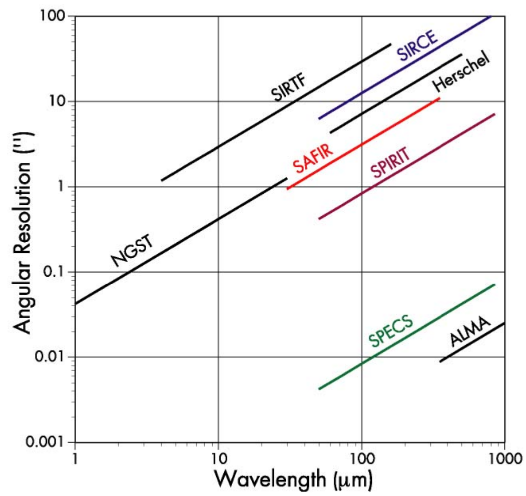
• The first stages of star and planet formation occur in cold cloud cores that are optically thick at <2µm, dominated by emission in diffuse outer shells at >500µm. SAFIR will offer angular resolution that will let us probe pre-planetary disks within these cores. This is unachievable with other IR missions.

• In cloud cores narrow OI is from infall and broad OI from outflows. $H_2O$ is a major coolant with a narrow component from a pre-planetary disk and a broad component from accretion. SAFIR has the spatial resolution to exploit these tracers (inaccessible with SIRTF) galaxy-wide much better than Herschel or SOFIA.

• SAFIR has the angular resolution (x10 higher than SIRTF, about 2” at 100μm) to see structure in debris disks around nearby stars. SAFIR will probe a warmer radial zone not readily accessible by ALMA at longer wavelengths. In addition, SAFIR will be able to study giant planets in the spectral range that dominates their luminosities.




Diffraction spot of planned far-IR observatories on a 15x15” simulation of the extragalactic background. The importance of SAFIR’s resolution in avoiding confusion is apparent.




The angular resolution as a function of wavelength is shown for important far-IR and submillimeter missions, including interferometers.

The science goals outlined above translate into the need for line sensitivity of $10^{-21}$W-m$^{-2}$ and arcsecond angular resolution in the far-IR. To provide the required measurement capabilities we envision SAFIR as a ~10m filled aperture telescope that operates at the natural background photon noise limit across the wavelength range from ~20 - 600μm. Background-limited performance is achievable if the optics are cooled to near 4K and next-generation detectors, with NEP < $10^{-19}$W-Hz$^{-1/2}$, are used.

## Section 2. Technical Approach and Methodology

### 2.1 Science Rationale Approach

Each of the many science goals outlined above requires slightly different aspects of a far-IR observatory and its instruments. Our approach to developing the science rationale for SAFIR, leading to the Science Summary document, was presented topic-by-topic in 1.2. To convert these science goals into observatory requirements, we will develop a comprehensive set of observations – a Design Reference Mission (DRM). The DRM will identify observations required to meet SAFIR’s science requirements, and will be used to set technical requirements for wavelength range, sensitivity, spatial resolution, field of view, and science instruments. These lead to requirements in aperture size and temperature, detector sensitivity and number, mirror quality, observatory location, field of regard and associated sunshade geometry, pointing knowledge, data volume for on-board storage, and observing efficiency. All candidate architectures will be evaluated against these requirements, with a minimum aperture size representing representing about an order of magnitude areal improvement over Herschel.

The mid-IR through submillimeter **wavelength range** is best for the extinction-independent study of star–ISM interaction, and the required technologies (in-space cryocooling, large telescopes, and sensitive detectors) are just now becoming available. Our study will consider the spectral matching of SAFIR to JWST at short wavelengths (e.g. 15-40μm), and to ground-based telescopes such as ALMA at long wavelengths (e.g. 350-800μm). It will match these science needs, which will evolve with the first SIRTF data, with new detector technology. The short wavelength limit will drive mirror quality, alignment and stability needs. At the long wavelength limit, our study will assess the importance of contiguous spectral coverage that is not available from ground-based telescopes because of narrow atmospheric opacity and thermal emission.

Our study will map the flowdown of science to the raw (e.g., point source) sensitivity for SAFIR. The **sensitivity** gains of SAFIR over previous generations of IR telescopes are so tremendous that judging from the history of the Great Observatory series of missions our expectations, while seemingly ambitious now, will end up defining a new domain of scientific achievement. Our study will consider the scientific importance of reaching the sky background limit and the importance of source confusion to SAFIR science at different relevant spectral resolutions. Our understanding of these issues will increase with the first observations from SIRTF. Our study will identify and examine sensitivity trades that pertain to telescope size. For a given-sized telescope, with fixed focal plane spot size , the required point-source sensitivity drives the observatory temperature, and thereby thermal management strategies in general.

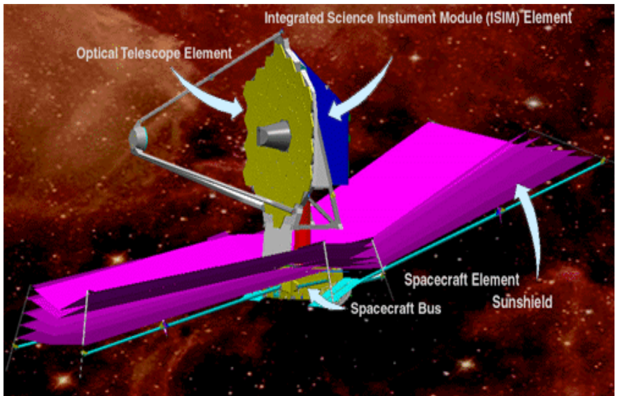
At these long wavelengths, the **spatial resolution** is determined mainly by the size of the observatory, so the architecture and scale are dependent on our needs here. While a defining vision for SAFIR is that of a high resolution far-IR observatory, our study will consider specific science goals of SAFIR in this context, and also the scientific match with observatories operating at nearby wavelengths. Following Stockman et al., who in 1996 conducted a similar study for JWST, we will consider image quality (resolution and contrast) from circular and non-circular mirror configurations, and how their different point source profiles impact the science. The impact of image reconstruction on the spatial resolution requirement, and the demands that it makes on observatory and instrument design, will be considered.

The **field of view** of SAFIR is a key issue that our study will address. The scientific importance of large surveys, for which a capability metric is the number of pixels that can be observed simultaneously, is a matter that determines both observatory architecture and detector array requirements. As IR detector array technology is advancing rapidly, huge increases in observatory capability can be foreseen at the focal plane itself. Our study will examine **instrument complements** for SAFIR. Advances in format size for IR detectors are happening rapidly enough that SAFIR will offer entirely new opportunities in this regard. While the need for broadband imaging seems undeniable, with huge scientific and public outreach appeal, satisfying the broad science requirements for SAFIR will require hard choices in instrument capability. In support of this, we include a **directed study by Ball Aerospace** that will develop a top-level instrument block diagram for SAFIR that is DRM-compliant, estimating TRL levels of key assembly technologies and recommending a lowest risk approach. It will estimate the mass, power, and volume of each instrument and of the scientific instrument total package and recommend strategies for managing instrument size and weight. A key issue to be resolved in this study is the importance of $\lambda/\Delta\lambda>30{,}000$ observations, which would demand investment in heterodyne technologies as well. We will carefully assess the scientific importance of a high-resolution spectrometer given the capabilities of ALMA, Herschel, and SOFIA.

### 2.2 Architecture and Implementation Approach

Our work has shown that several space systems architecture concepts offer SAFIR clear scientific opportunities. These will be developed in our Concept Review document. Our study will look carefully at these in the context of the DRM, and in the context of technology readiness and trades. It will consider a range of architecture related issues, evaluating structure design, materials, performance analysis, mechanisms for deployables including their packaging in a fairing, thermal management (both passive and active), and dynamical issues relating to structures and deployment requirements. Our Concept Review will address space system architecture in general, science instrumentation, infrastructure, and potential roles of astronauts.

A modified JWST architecture is one starting point for SAFIR trade studies, and has already undergone a GSFC IDC study (July 2002). The JWST includes hexagonal deployable primary and secondary mirrors, a deployable sunshield, and a deployable tower connecting the warm spacecraft bus to the telescope, which resides at Sun-Earth L2, and passively cools to ~35K. The line of sight can be in any direction in the range of 85 to 140 degrees from the Sun. Hydrazine thrusters for gyro despin do not contaminate the mirrors because they are on the warm side of the sunshield. The spacecraft bus uses existing technology to provide solar power, command and data handling, on-board memory, and telemetry. Modifications for SAFIR include additional radiative cooling and active cooling for the telescope (from 35K down to ~4K) and the sensors, as well as larger mirrors. This general architecture may offer important operating temperature-versus-size trades, and our study will evaluate these.

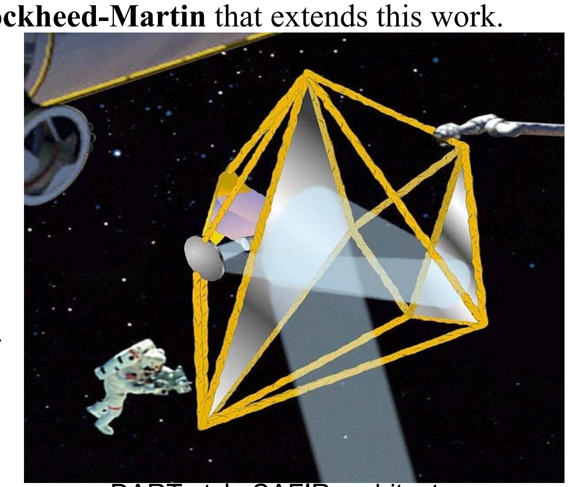


Modified-JWST style SAFIR architecture

In support of this, we include a **directed study by Northrop-Grumman** on a 4K folded mirror JWST-like telescope, an optimally radiatively cooled JWST-like telescope and a much larger passively cooled TPF coronographic concept telescope (but without the coronograph) with card-deck platter-deployment. This will include a temperature and emissivity map for each of these three telescopes, cooling rate analysis, and development of parametric relationships between telescope cost, size, and temperature.

A second concept that will be investigated closely is the Dual Anamorphic Reflecting Telescope (DART). The new DART system is dramatically lower in aperture/mass ratio and potentially simpler to deploy than segmented mirror systems. Where a conventional telescope uses a single parabolic mirror, DART uses two ultralight reflectors made of membranes stretched on a rigid frame. Each of these mirrors has cylindrical symmetry (concave in one direction instead of two). The alignment of the two reflectors is critical to the performance of the system, but an arrangement of six adjustable rigid struts connecting the two reflectors completely constrains all degrees of freedom while allowing the adjustment of the relative orientation of the two reflectors. Initial testing of a small prototype has been very encouraging (40µm diffraction limit has been achieved), and a 2 x 4 meter model is now under test in a collaboration between JPL and Lockheed-Martin. The DART concept studied by the NEXT program produced a JPL Team-X study that included considerable thought about deployment, with and without astronauts.

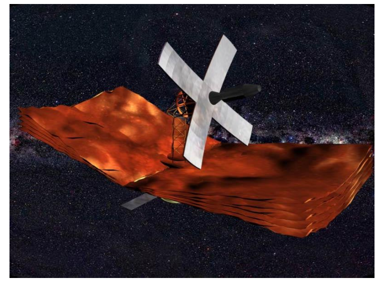
This proposal includes a **directed study effort by Lockheed-Martin** that extends this work. Lockheed will study critical technologies that represent high risk or need significant development. It is anticipated that this study will include thermal control, gravity release effects, on-orbit figure adjustment and metrology, vibration isolation and pointing control. In addition, Lockheed will review techniques for optics membrane reflector deployment, and launch survivability, and explore options for 15-25m aperture sizes.


DART style SAFIR architecture

Finally, we acknowledge the substantial heritage from the Large Deployable Reflector (LDR) effort of a decade past. Many of the technical hurdles that faced this observatory have been since eliminated. Interestingly, LDR evolved into an international mission that was then successfully scaled back in size to what is now Hershel. In this context, we note that our team includes a UK collaborator (Griffin) who will keep us apprised of **non-US planning efforts** in general, and specifically for ESA, on the far-IR and submillimeter front.

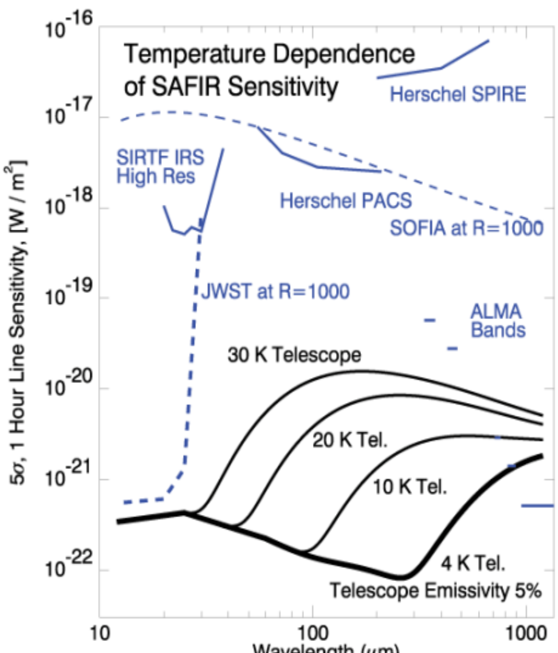
Our study will pay special attention to optimal **orbital venues**. It is impossible to achieve the needed temperatures in LEO, so a prime target is L2 – the location of WMAP and the destination for JWST. It is close enough for high RF telemetry rates, and provides the needed shielding geometry. The Earth-trailing driftaway orbit of SIRTF avoids the need for station-keeping maneuvers (the L2 orbit is unstable), but requires more advanced telemetry. Geosynchronous orbits would require improved sunshields and much more powerful coolers by comparison. None of these orbits are presently compatible with in situ servicing by astronauts. Orbits much farther from the Sun would reduce the zodiacal light background and improve sensitivity, but may require special power sources.

The baseline configuration of the SAFIR calls for a roughly circular **aperture shape**, independent of mirror technology. This offers the most compact image, ultimate sensitivity for a fixed mirror area, and matches the typical square symmetry of detector arrays. However, at long wavelengths, image contrast may be more important than angular resolution. Resolution might be improved with non-circular symmetry, at cost of asymmetrical instantaneous images. Symmetrical images could be recovered by combining observations taken at many roll angles. We will search for an observatory configuration compatible with this mode, and will examine the scientific drivers for it.



Sparse aperture (non-circular) concept for SAFIR primary offers added spatial resolution.

Every aspect of SAFIR must contribute to achieving an unprecedentedly large and cold telescope. The **thermal design** is thus the most important, and most complex, part. A successful thermal design must include the following key ingredients: maximal use of radiative cooling, efficient isolation, (both radiative and conductive, between warm and cold parts), and the use of active cryocoolers to supplement radiative cooling. Studies suggest that temperatures of ~10 K may be achieved radiatively at L2. It can be seen from the plot below that a 4K SAFIR is background limited on the zodi and CMB. A central question in our mission concept study, therefore is: What are the limits of thermal isolation and radiative cooling, i.e. how low a temperature can be achieved passively? The answer will depend on the orbit, and on the structure and materials of SAFIR, which in turn depend on size and thermal shields. This will determine the amount of active cooling required, and the kind of active coolers that must be developed. A key tradeoff is between mirror diameter and temperature. The larger the mirror, the more photons are collected. But the dependence of SNR on mirror size depends on whether the dominant source of noise is from the detectors, telescope, diffuse sky backgrounds, or source photon statistics. Presently this tradeoff is hampered by our poor knowledge of the source density in the far-IR. Fortunately, SIRTF will change this situation dramatically during the study. The number of design variables pertinent to the overall thermal design is huge, well beyond the possibility of an exhaustive search. As described above, we will use a different approach, starting with the architectures described above.




At a telescope temperature of 4K, SAFIR is background limited on zodi and CMB. Even well above 4K, it still vastly outperforms contemporary missions.

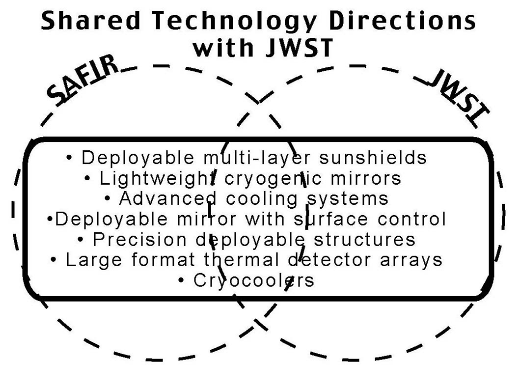
The SAFIR **integration and test** concepts will be developed based on those of the JWST and SIRTF missions. Ideally SAFIR will be tested on the ground as it will fly. Our study will consider infrastructure and constraints assumed in place at the time of implementation. The largest available test chamber is the Plumbrook facility at NASA's Glenn Research Center. Chamber modifications that would be required for SAFIR's lower temperature will be evaluated during this study. Changes may also be required in the methods used to compensate for gravity, since the larger SAFIR may be supported differently than JWST. During the study experts from SIRTF and JWST will evaluate a range of I&T questions.

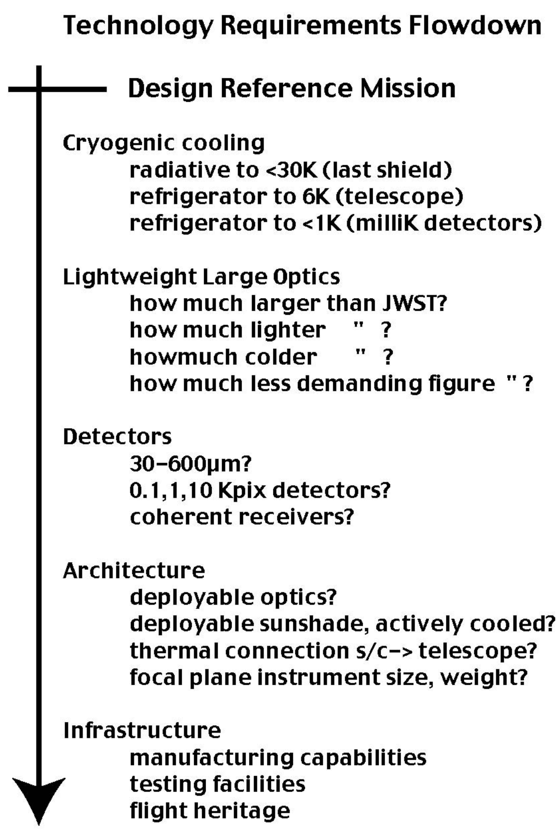
Based on work done to date, it is clear that a large, cold far-IR and submillimeter telescope can be flown in the next decade. The key task in our study is to construct from among discrete possibilities an overall design concept that maximizes performance through innovation while minimizing cost and risk.

SAFIR's **power system** will be sized to meet observatory needs, which are dominated by the active cooling system. Cryocooler efficiency estimates lead to a ~4kW budget, which can be provided at L2 using solar panels of area <20m$^2$ mounted to the spacecraft bus on the sun-facing side. The design will be evaluated during the concept study as the cryocooler technology and thermal control design mature. We will consider the availability of nuclear power sources, both radioisotope thermal generators and space fission reactors. These could be highly enabling even though the SAFIR baseline does not require nuclear power.

### 2.3 Enabling Technologies

SAFIR places challenging demands on detector, cooled optic, sunshade and cryocooler technologies that must be carefully managed to achieve flight mature systems. Its unique capabilities will be realized at the cost of a deliberate and sustained investment by both Code S (including R&A) and Code R (e.g. MSMT). **We will develop a Technology Roadmap** that will address the science driven needs of SAFIR with reasonable cost/schedule requirements. Although the science objectives are unique, there is significant technology synergy with other present and future code S missions such as TPF, JWST, and the Inflation Probe. The SAFIR technology roadmap will discuss these synergies and recommend an approach that will maximize the return on investments. These demands are discussed in more detail below in approximate priority order. Our team was carefully chosen for insight into mission and technology needs, as well as familiarity with both Code S and R technology programs. Our Technology Roadmap will thus be well suited to upcoming roadmapping efforts. We will identify, in particular, areas not supported by industry, DOD or other NASA applications, and where technology needs call for major advances in the state of art.

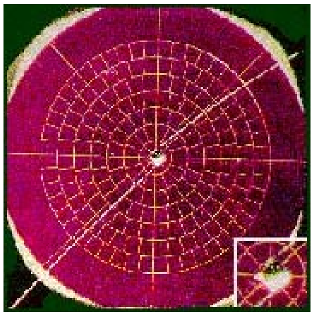


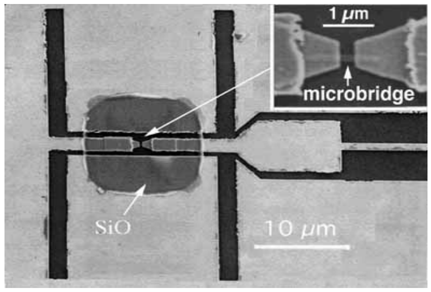




NASA's Aerospace Enterprise (Code R) invests in a number of early technology developments under the Enabling Concepts and Technology (ECT) Program. At a high level requirements are fed from Code S to ECT, which then invests in low TRL technology to enable high priority missions. Under ECT the Large Space Systems Project and the Advanced Measurement and Detection Project pursue technology consistent with the SAFIR needs. Our Technology Roadmap will address the low TRL technology needs which can be presented to ECT. With the help of a Code R collaborator (Dooley), we will review the technology tasks currently ongoing to identify candidates for transition funding to higher TRL development.

**Detectors:** The full promise SAFIR will only be realized if detectors of matching capabilities are available. SAFIR science will require significant effort in detector development, and an important effort under this proposal will be identification of detector needs. It has been well demonstrated that early investment in key technologies can pay large dividends in cost and success. Our study will flow down the science requirements for SAFIR into detector technology needs.

For example, in order to take advantage of the low background from SAFIR, detectors with NEPs less than a few x $10^{-19}$ W $Hz^{-1/2}$ will be needed for cameras, and lower for spectrometers.






Large format infrared arrays (such as the SiN "spider web" bolometer design shown at left) promise to multiply the productivity of SAFIR. Low noise oscillators and efficient mixers, as shown at right will provide new opportunities for high resolution studies with SAFIR. Focused technology investments will allow us to realize these opportunities.

Both imaging and spectroscopic observations will require large, sensitive, and high dynamic range detector arrays. While remarkable progress has been made in producing very large arrays for $\lambda$<40 μm, significant effort will be needed to produce the desired systems for the far infrared and submillimeter. To support wide-field deep surveys or high resolution spectroscopy, arrays in excess of $10^4$ elements will be needed. Such element numbers have a large multiplicative effect on observatory productivity. The development of such large focal plane arrays in the far-IR and submillimeter bands represents a significant leap beyond the current state of the art.

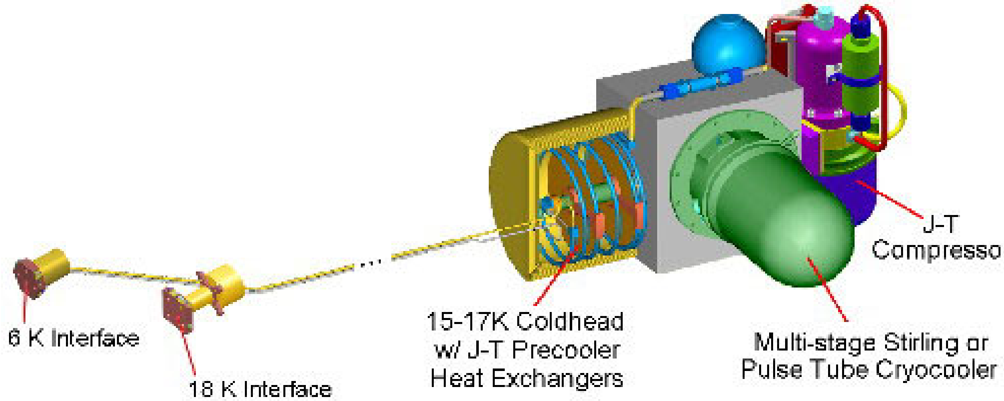
The detector needs for these wavelengths have been addressed in OSS strategic planning efforts by the IR, Submm, and Millimeter Detector Working Group, (chaired by team CoI E. Young); a number of the technologies, including superconducting and semiconducting bolometers and photoconductors, are being investigated under NASA funding. During this study we will assess them in the light of our concept and identify gaps. We will develop a SAFIR-specific detector technology roadmap.

**Sunshades:** Radiative cooling is a crucial part of SAFIR's thermal control. Sunshades use no power but intercept the majority of the thermal load. Optimized shielding of a Sun-illuminated observatory can reduce the thermal load by up to six orders of magnitude. We will investigate the status and progress of the technology required for this, including multi-layer designs (including numbers of layers and internal angles), deployability, and material properties. Thermal physics leads to a rapid drop of thermal radiator efficiency versus temperature, and the lowest achievable temperature can be affected by proper design. Given the limited scope of this investigation, we hope to narrow the field of promising technologies for radiative cooling. We will produce an estimate for the performance requirement for SAFIR's sunshield, and can be used as an input to the upcoming Space Technology-9 in-space validation effort.

**Cryocoolers:** Optimized cryocoolers will be a critical part of both SAFIR and Life Finder type missions. They will be required not only for the sub-Kelvin focal planes supporting low noise detector operation, but also to achieve the low thermal background required by the science objectives. We will investigate and report on unique requirements, their priority and sensitivity of design to each, and key technology risks and uncertainties. The ACTDP is taking a big step in this direction, but we will need even higher capacity, more efficient coolers for SAFIR. Alternative approaches will be identified, where applicable, and we will provide an approach for validation and or demonstration.

**Cryogenic Optics:** Our study will report on cryogenic mirrors, which are an enabling technology for SAFIR regardless of its eventual design configuration. Technical maturity of the process to manufacture and validate them and associated cost and schedule issues will be significant contributors to SAFIR's eventual flight architecture. Areal density <10 kg/m2, <10K temperatures, and <1μm surface accuracy pose important technological challenges.

Our Technology Roadmap will include a review of mature cryogenic mirror technology in order to mitigate technical, cost and schedule risk early enough in the program to influence the architecture selection. A **directed study by the MSFC Space Optics Manufacturing Technology Center (SOMTC)** is included in this study effort under a study collaborator (Stahl, JWST Mirror Technology Lead). This effort will take full advantage of the lessons learned on the JWST mirror effort. After the Concept Development team (working closely with the science team) translates science requirements into engineering specifications, SOMTC will perform a




Schematic of cryocooler system being developed under the NASA ACTDP initiative.
This staged cooler can be used for cooling of the SAFIR focal plane and telescope assembly

technology gap analysis to assess the technical maturity of the engineering specifications. After an assessment of the current state-of-art and technology investments being made by all governmental agencies, a roadmap will be prepared to demonstrate SAFIR traceable mirrors at TRL-6 with attention to development risks and the difficult question of integration and test. For example, researchers at the Air Force Research Laboratory's Directed Energy directorate were recently able to produce a 1m-diameter mirror, made of a thin-film membrane material. This optical-quality polyamide mirror, about the thickness and flexibility of kitchen plastic wrap, was more than three times larger than the biggest membrane mirror previously possible. As noted above similar efforts are ongoing with DART. Our cryogenic mirror study plan will make maximum possible use of industry capabilities. New substrate materials such as SiC and MgGr will likely be considered as well as new fab processes such as replication. Membrane technologies will be evaluated as well. The ultimate goal is to minimize cost, schedule and technical risk for the manufacture, integration and test of SAFIR cryogenic optics.

**2.4 Deployment**

Our study will report on deployment designs, including transportation to operational location and assembly as required. We will review designs developed for JWST and other missions to identify advantages or serious technology needs. Choices include the 3-leaf adopted for JWST, a flower petal design, various robotic assembly approaches that can pack many mirror segments into small volumes, the HARD (High Accuracy Reflector Deployment) method developed for other government agencies, and radically different methods suitable for the DART concept. As with JWST, it is likely that the deployment method would be developed and proposed by the eventual prime contractor and would be competition-sensitive. SAFIR team members will pursue such concepts and will report on the relative merits of alternative approaches.

We will consider roles for astronauts and robots in assembly and on-orbit checkout. On the basis of visionary plans by the NEXT team, such roles may minimize risk and be highly enabling even though the premise of the baseline SAFIR plan does not require them. In this context, as well as others (e.g. I&T, assurance, maintenance, operations servicing), our proposal includes a **directed study effort by Boeing** to map human in-space capabilities onto SAFIR-specific needs. This study will identify the technology required to support human presence and participation, cataloging the pros and cons of human participation, as well as a ROM cost difference between human-assisted and autonomous options. It will consider the complementary role played by robotic assistants, to optimize the mix of robots and humans in task performance. Our study team includes collaborators at JSC (Grunsfeld and Ward) who will competently evaluate this report. With their key efforts on NEXT, they will ensure strategic consistency of the astronaut aspects of our Concept Review with the direction of the Space Architects Office.

**2.5 Operations**

A JWST-like operations scenario is envisaged for SAFIR, an assumption that the study will evaluate against the DRM. The instrument complement and the importance of survey-mode observations will be key factors. This will include consideration of FOV constraints that are driven by Sun angle and concomitant thermal control. The study will consider the level of autonomy that the spacecraft will require, determined in part by the bandwidth of the communication segment, though the space segment can be largely autonomous after the commissioning period. While the communication segment baseline for SAFIR is the set of DSN antennas, a dedicated ground station would also meet SAFIR's modest downlink needs if a larger antenna and/or higher transmitting power were implemented on the Spacecraft. The ground station options will be re-evaluated during the study to identify solutions with lowest overall mission cost. Our study will consider scenarios for servicing of SAFIR, perhaps involving return-to-Earth from L2 and warmup followed by instrument replacement.

### 2.6 Operations Assurance

SAFIR will review operations assurance, including system resilience and maintenance. Proven design techniques such as thermal system redundancy (using cryocoolers in parallel, providing extra sunshield layers) will be evaluated. Our work will involve a preliminary probabilistic risk assessment to see where redundancy will most improve mission success. We will evaluate potential roles for astronauts in SAFIR technology demonstration, including conducting on-orbit tests of deployment systems, aperture control techniques, and cooling technologies.

### 2.7 Safety

Our study will review safety issues associated with candidate implementations of SAFIR. As an astronomical mission, planetary protection requirements are not applicable. Since thermal design requirements drive the mission design away from an Earth orbit, end of mission safety issues may ultimately be minimized as well. Concepts which include pressurized or cryogenic systems, astronaut involvement, and/or alternate power sources would, however, have associated system and occupational design issues. Ground testing and test facilities, launch facility, range, and operational (especially near-Earth operations) safety requirements will be considered.

## Section 3. Impact

As the most comprehensive description to date of the SAFIR vision mission, the impact of the proposed work to the state of knowledge of the field will be highly significant. This study will further develop the science, architecture, implementation approach, technology needs, deployment, operations and safety approach, beyond previous efforts.

The work will sharpen the understanding of SAFIR in the interest of scientific programming and planning. and is intended to be maximally useful for future strategic planning efforts and integration of long range Agency-wide planning. The integrated approach that we take will specifically guide OSS's (as well as constructively contribute to Aerospace Technology's) long term technology investments in order to be fully responsive to priority scientific goals.

## Section 4. Relevance

As described in 1.1, the proposal develops key understanding for a mission that is consistent with many scientific goals in agency and community strategic plans. In doing so it uses new technology capabilities to meet and answer profound and current scientific questions. SAFIR is squarely on both the scientific and technological path to longer range vision missions.

## Section 5. Work Plan

The proposed study will refine the SAFIR mission concept. It will hone the science case, distilling key objectives and distinguishing it from previous and queued missions. It will show how NASA's current investments can be extended to create advanced new capabilities, and it will define a roadmap to guide technology. The study will also consider the role of astronauts as a means to enhance the science objectives.

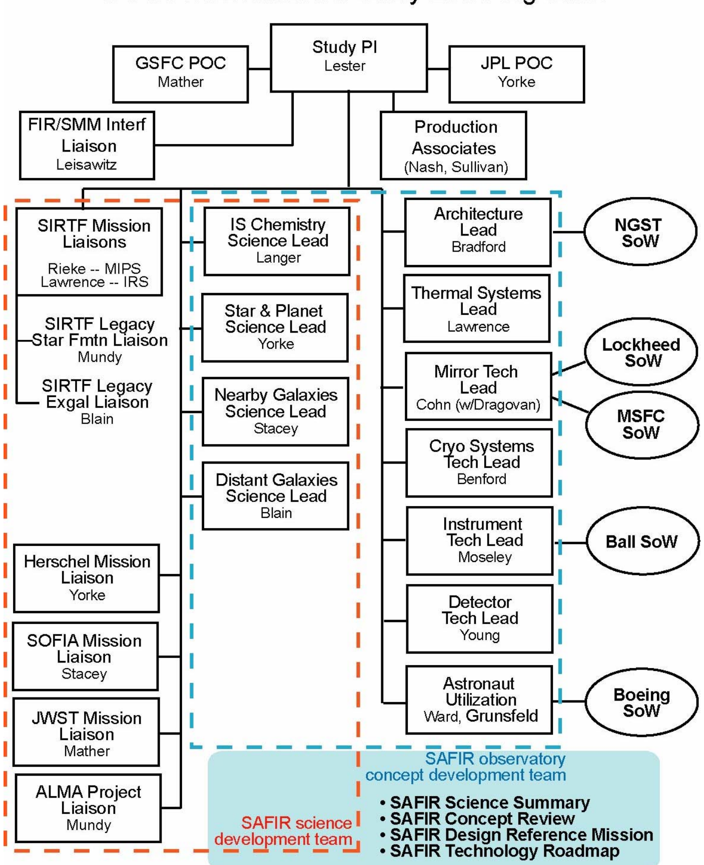
Our team includes a PI and CoIs from academia, JPL and GSFC. They have key roles in contemporary IR missions, ensuring firm linkage with SAFIR. Our technology team is qualified to guide readiness assessment and roadmapping, and see to it that science goals are accurately translated into engineering specifications. Our collaborators cover extra programmatic bases and add key operations and engineering perspectives; they include staff at both MSFC and JSC. With committed involvement from four centers, NASA resources will be efficiently engaged and leveraged. We have engaged Ball, Boeing, Northrop-Grumman, and Lockheed in directed study efforts that support the work, and consider them part of our team. The enthusiasm of the team to this Vision Mission leads to commitments that are, in significant part, contributed time.

Our CoIs are assigned roles in three categories. (1) Science Leads handle science case development and are tasked with promoting community dialog SAFIR's role for enterprise science priorities. They establish the scientific “tall goals” and generate the Science Summary and Design Reference Mission. (2) Technology Leads will translate science requirements into technology requirements, provide oversight for industry study partnerships, and generate the Technology Roadmap. This establishes the corresponding “tall poles”. In doing so, they will lead the production of the Concept Review document. (3) Mission Liaisons, with “insider” status on closely relevant missions, will guarantee alignment of SAFIR goals with expectations for and results from them. Liaisons are provided for SOFIA, Herschel, JWST, and ALMA, as well as SPECS, with four Liaisons for SIRTF – two for Legacy programs that will profoundly impact the SAFIR science mission, and two for each of the SAFIR-relevant SIRTF instruments.

While Leads and Liaisons have single-point responsibility for designated efforts, the team as a whole will contribute to them. Our org chart is shown below, where two integrated teams – Science, and Observatory Concept Development, are delineated. These teams reveal, through the study flowchart below, the expected contributions of personnel to the proposed effort. This is supplemented by the attached table, which lists team members in the collaborator category, and their expected contributions. We note that while this organization chart would not be suitable for a large-budget study owing to the lack of a formal study manager, we believe that the limited budget and requisite flexibility of the participants around their “day jobs” requires this unconventional arrangement. The flowchart is intended to highlight the inputs into this effort. A study schedule is also shown below that provides process alignment.

Our work plan includes essential team travel. A west coast team meeting will be held in addition to weekly telecons. A team rep will site visit each industry partner at mid-effort to monitor contributions. As required by the NRA, the PI will report on our results to NASA HQ. A team rep will report to the community at an American Astronomical Society meeting (1/2005, San Diego), as well as the “Beyond SIRTF” workshop now scheduled for Spring 2004.

SAFIR Vision Missions Study Effort Org Chart



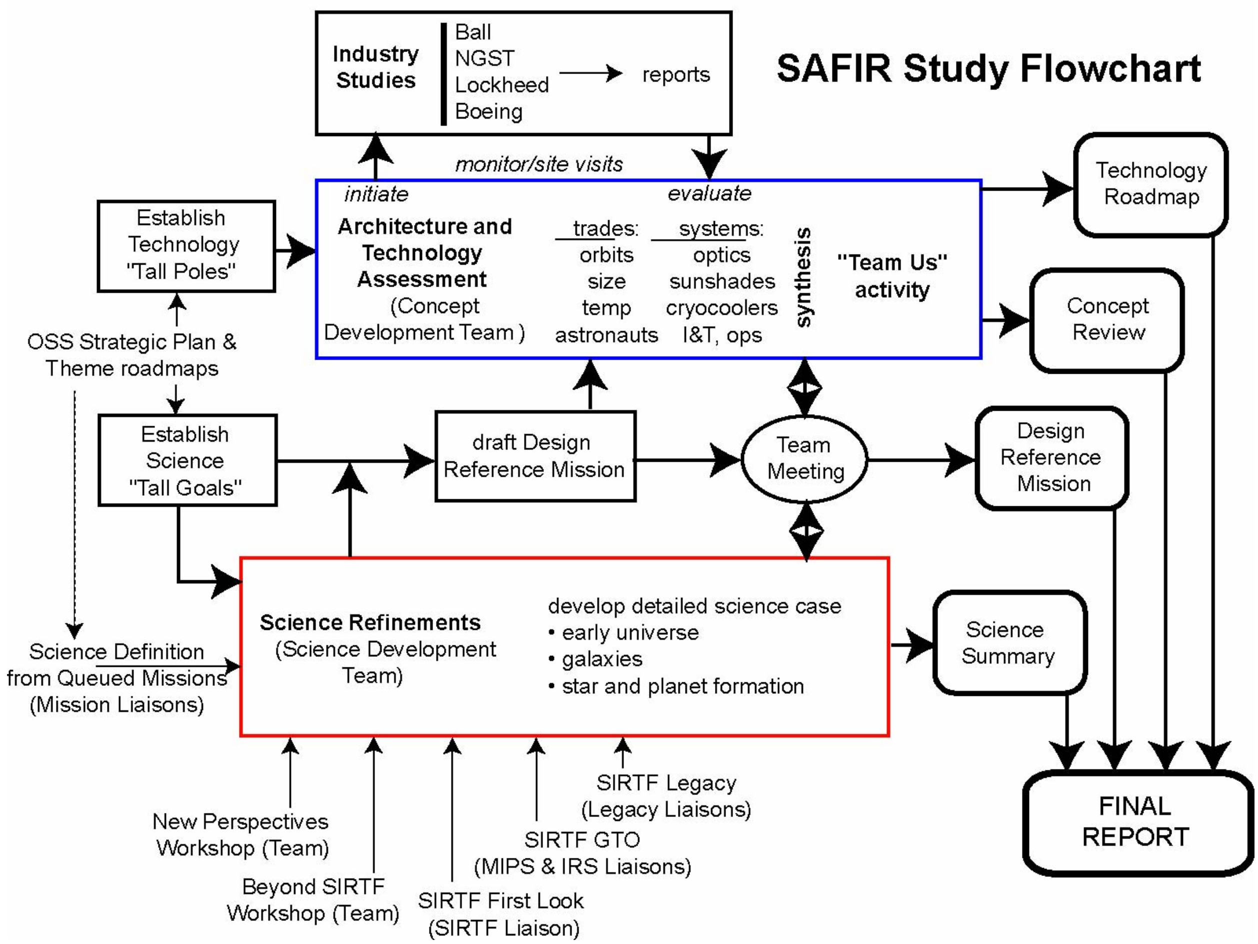

| Study Collaborators | |
|---|---|
| Eri Cohen | cryo optics |
| Jennifer Dooley | DART, Code R |
| John Hong | tech roadmap |
| Matt Greenhouse | sci inst system |
| Matt Griffin | intl liaison |
| John Grunsfeld | astronaut review |
| Bob Menzies | proj management |
| Phil Stahl | cryo optics |
| Brenda Ward | astronaut review |

The formal work packages with four industry partners will augment our study effort. These partners were chosen based on their expertise with SAFIR needs, and have generously agreed to provide us with team budget-seeded B&P enhanced efforts (NGST chooses to use their own funds exclusively, so is a zero-cost effort.) NDA agreements will be used as required, but with the understanding that conveying results to NASA is a primary task. Early versions of the draft DRM will be used to initiate these industry studies. We propose partnering with the MSFC Space Optics Manufacturing Technology Center. This will connect SOMTC with key science requirements. Agreed upon SOWs are appended in Budget Summary.

Our study includes modest effort from Production Associates at both JPL and GSFC to ensure that the results of the study are edited and organized in a manner that is useful to NASA and the community. These results that comprise the Final Report are summarized below.

The Technology Leads will work closely with technical staff at GSFC and JPL to develop the Technology Roadmap and contribute to the Concept Review documents. GSFC and JPL have ongoing investments directed toward SAFIR technologies, and these centers offer us important human resources with regard to SAFIR needs. Letters from JPL and GSFC institutional leads (see attached in the Commitments section) demonstrate explicit support for such leveraging. While we do not quantify the center resources that would leverage this study effort, we will apply through internal programs for additional support totaling at least several FTEs. We anticipate at least several FTEs will be committed.

Finally, we propose a focused **JPL Team X study** that will help formalize our efforts. The main architectural studies and trades will result in a core design for SAFIR that satisfies the science requirements. The next step use the Team X design process to (1) complete the conceptual design, adding systems and subsystems where SAFIR is not pathbreaking but which are essential to the mission (2) verify that the core conceptual design is feasible, (3) review the technology roadmaps to ensure that all areas where technology development is required have been identified, (4) identify additional areas of technology development that might offer significant cost savings.




Team X will be joined at JPL by key personnel from the GSFC IMDC team for this exercise. We refer to this combined team as "Team Us" to emphasize the multi-center effort. This combined team can take full advantage of the experience of the IMDC in studying a JWST-heritage preliminary SAFIR design (7/2002 study), but without the drawback of repetition, and brings in the new perspective of Team X. This pathbreaking interaction of the two teams exemplifies the multi-center spirit of the SAFIR team, and offers real synergies between two premiere science and engineering centers. The output will be a complete mission concept, with the first level of engineering analysis completed. The Team X administration has been contacted about this effort.

We will hire a student through a JPL Summer Employment Program. The student will learn about SAFIR, and missions such as SIRTF, JWST, and ALMA that provide scientific and engineering context. The student will provide specific web linkages from them to the SAFIR site, and will help do web updates that interpret and reflect study progress. The culmination of this experience will be participation in the Team Us activity. This will provide an overview in aerospace engineering and astrophysics mission planning. The student will write a short report describing his/her experience, which will be posted on the SAFIR website. CoI Lawrence will mentor. In addition, CoI Blain will use student help on extragalactic modeling efforts.

The University of Texas PI is responsible for supervision of work and will participate in product development. "Institutional" CoIs for JPL and GSFC are identified; and will be POCs for center obligations. This fully functional multi-center team has worked productively together on SAFIR for several years, was responsible for initial concepts, and brought those concepts to the SScAC, Decadal Panel, and greater community. As described, the product will be a comprehensive Final Report, consisting of the seven sections described in the NRA, from the following four products:

• SAFIR Science Summary: This will be the definitive document for SAFIR science, presenting this science in the context of OSS strategic planning and with operating and queued missions.

• SAFIR Design Reference Mission (DRM): This will present, in a manner consistent with the Science Summary, a strawman plan for achieving SAFIR science..

• SAFIR Concept Review: This will review DRM-compliant observatory architectures. Enabling technologies will be identified. Elements of benefit/risk, and human-robotic operations for assembly, integration & verification, and maintenance will be addressed.

• SAFIR Technology Roadmap: This will review the readiness levels of applicable SAFIR technologies, with particular attention to technologies that are important to all design options. It will recommend SAFIR technology investment that will best achieve OSS strategic goals.

## SAFIR Study Schedule

| ID | Task Name | Duration |
|---|---|---|
| 1 | **Science Definition** | **220 days** |
| 2 | Draft Science Reqts | 30 days |
| 3 | Draft Design Reference Mission | 30 days |
| 4 | Final Science Reqts | 30 days |
| 5 | Final Design Reference Mission | 30 days |
| 6 | Science Summary Report | 40 days |
| 7 | **Telescope & SI Studies** | **90 days** |
| 8 | JWST Concept | 90 days |
| 9 | TPF Concept | 90 days |
| 10 | DART Concept | 90 days |
| 11 | Instrument Concept Study | 90 days |
| 12 | **Mission Trades** | **80 days** |
| 13 | Telescope Size & Temperature | 40 days |
| 14 | Orbit | 30 days |
| 15 | Astronaut Roles | 70 days |
| 16 | **Mission Definition** | **85 days** |
| 17 | Architecture Synthesis | 30 days |
| 18 | "Team Us" Study | 25 days |
| 19 | Mission Concept Document | 30 days |
| 20 | **Technology Roadmaps** | **75 days** |
| 25 | Final Report | 40 days |
| 26 | SAFIR Study Complete | 0 days |