Single Aperture Far-Infrared Observatory (SAFIR)

Paul M. Harvey[a], George H. Rieke[b], D. F. Lester[a], and Dominic J. Benford[c]

[a]University of Texas, Astronomy Dept., Austin, TX 78712, USA
[b]University of Arizona, Steward Observatory, Tucson, AZ 85731 USA
[c]Infrared Astrophysics Branch, NASA-Goddard Space Flight Center, Greenbelt, MD 20771 USA

ABSTRACT

Development of large, far-infrared telescopes in space has taken on a new urgency with breakthroughs in detector technology and recognition of the fundamental importance of the far-infrared spectral region to cosmological questions as well as to understanding how our own Solar System came into being. SAFIR is 10m-class far-infrared observatory that would begin development later in this decade to meet these needs. Its operating temperature ($\leq$ 4 K) and instrument complement would be optimized to reach the natural sky confusion limit in the far-infrared with diffraction-limited peformance down to at least the atmospheric cutoff, $\lambda \gtrsim 40\mu$m. This would provide a point source sensitivity improvement of several orders of magnitude over that of SIRTF. SAFIR's science goals are driven by the fact that youngest stages of almost all phenomena in the universe are shrouded in absorption by and emission from cool dust that emits strongly in the far-infrared, 20μm - 1mm. The earliest stages of star formation when gas and dust clouds are collapsing and the beginnings of a central star are taking shape can only be observed in the far-infrared. Likewise, the cool dust that will eventually form planetary systems, as well as the cool "debris" dust clouds that indicate the likelihood of planetary sized bodies around more developed stars can only be observed at wavelengths longward of 20μm. The most active galaxies in the universe appear to be those whose gaseous disks are interacting in violent collisions. The details of these galaxies, including the central black holes that probably exist in most of them, are obscured to shorter wavelength optical and ultraviolet observatories by the large amounts of dust in their interstellar media. Early stages of galaxy formation appear to result in powerful sub-mm emission indicative of substantial metal enrichment early in the history of the universe. Finally, the warm gas of newly collapsing, unenriched galaxies should reveal itself in hydrogen emission at these long wavelengths. The combination of strong dust emission and large redshift ($1 < z < 5$) of these galaxies means that they can only be studied in the far-infrared and sub-mm where SAFIR will provide the sensitivity and angular resolution to peform imaging and spectroscopic studies of individual galaxies in the early universe. The main drivers on the telescope are operating temperature and aperture. SAFIR can take advantage of much of the technology under development for NGST. Because of the much less stringent requirements on optical accuracy, however, SAFIR can be developed at substantially lower cost.

Keywords: Far-Infrared, Telescope, Space

1. INTRODUCTION

The Single Aperture Far-Infrared Observatory has been recommended by the community consensus in the National Academy of Sciences Astronomy Decadal Review[1] as a high priority scientific and technical successor to NGST and SIRTF. SAFIR is envisioned as a 10m-class far-infrared observatory that would begin full-scale development late in this decade, for launch in ~2015. This recommendation recognizes the exciting science opportunities offered by the promise of a dramatic increase in sensitivity and angular resolution of a facility like SAFIR in the far-infrared spectral region. SAFIR "will enable the study of galaxy formation and the earliest

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Further author information: (Send correspondence to P.M.H.)
P.M.H.: E-mail: pmh@astro.as.utexas.edu, Telephone: 1 512 471 3452
G.H.R. : E-mail: grieke@as.arizona.edu, Telephone: 1 520 621 2832
D.F.L. : Email: dfl@astro.as.utexas.edu, Telephone: 1 512 471 3442
D.J.B. : Email: dominic.benford@gsfc.nasa.gov, Telephone: 1 301 286 8771

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."[1] The SAFIR concept embraces that of other large far-infrared telescopes that have been recently proposed, such as FAIR, and DART and encompasses most of their science objectives.

Development in the far-infrared has lagged relative to the optical, near-infrared, and radio portions of the spectrum for two main reasons: the need to be above most or all of the Earth's atmosphere because of very strong absorption features of water vapor, and the need for very low temperature telescopes and instruments to reach the natural background limits of sensitivity at these wavelengths. In addition, large apertures are required to achieve the angular resolution needed for comparison with modest optical and near-infrared studies. As a result of efforts on other large space telescopes, strategies to address these needs effectively are now in hand.

The field of far-infrared astronomy began in the late 60's and 70's with balloon, aircraft, and sounding rocket explorations of the astronomical sky.[2] The best combination of sensitivity and angular resolution was provided by NASA's Kuiper Airborne Observatory with a 0.9-m telescope operating at stratospheric temperatures. With the IRAS[3] all-sky survey in the 80's using a 57cm liquid-helium cooled telescope, the wealth of phenomena illuminating the far-infrared sky became apparent. Since that time, though, only modest improvements in sensitivity were achieved with ESA's Infrared Space Observatory[4] (ISO) that took advantage of detector developments made since IRAS. The current decade will see the launch of three new observatory-class far-infrared facilities: SIRTF, SOFIA, and the Herschel Space Observatory, each of which will provide substantial improvements in sensitivity and/or angular resolution. Each, however, is also clearly far from the current state-of-the-art in aperture and sensitivity for different reasons. SIRTF, with its entirely liquid helium cooled telescope, will easily reach the confusion limit on the sky in the far-infrared, but because of its modest 85cm aperture, this confusion limit is substantially above that of the other two facilities. SOFIA, which will begin operations in late '04, will have three times the aperture of SIRTF, but because it is operating at ambient stratospheric temperatures, it will never approach the sensitivity of cryogenic space observatories. Late in the decade the Herschel Space Observatory will provide improvements in both aperture, 3.5-m, and operating temperature, $T < 80K$. At the long end of the far-infrared spectrum, $\lambda > 100\mu m$, Herschel will reach a much lower confusion limit on the sky than SIRTF or SOFIA with integration times, however, of order a few hours and focal plane arrays of a few $\times$ 10^2 - 10^3 pixels. Herschel, too, though is handicapped because its operating temperature is still so much greater than the equivalent brightness temperature of the natural sky background at these wavelengths. While SIRTF will probe the faintest and most distant sources in the universe, SOFIA and Herschel will view the brighter sources with higher spatial resolution. Even before these new infrared observatories fly, it is clear that their scientific and technical trajectory points directly at the need for an observatory like SAFIR.

SAFIR will use state-of-the-art technology in lightweight optics, cryogenic cooling, deployable structures, and the most recent detector technology to enable large sensitivity improvements over these previous missions together with much needed improvement in angular resolution. For example, the improvement in mapping speed, which is proportional to pixels/sensitivity^2, will be $\sim 10^6$ with 2 orders of magnitude more detectors and a 2 order of magnitude improvement in sensitivity. We describe the compelling science drivers for this mission in the following section. Following that, we then discuss the drivers on telecope and detector specifications that result from the science requirements and our confidence in their achievability. Finally, we briefly describe the current state of definition of this observatory and status of the project.

2. SCIENCE DRIVERS

2.1. Overview - The Role of the Far IR/Submm

Regardless of the original emission process, cosmic energy sources glow in the far-infrared and submillimeter. The continuum emission is due to the incredible efficiency of interstellar dust in absorbing visible and ultraviolet photons and reemitting their energy. The appearance of the early Universe, of active galactic nuclei (AGN) and starbursting galaxies, and of star forming regions is transformed through suppression of the visible and ultraviolet and augmentation of the far-infrared and submillimeter. Low-lying far-infrared fine structure lines are the major coolants for interstellar gas. Molecular transitions in this spectral range carry the signature of conditions in warm and dense interstellar clouds where stars and their solar systems form. Thus, we must look in the far-infrared and submillimeter for clues to the underlying processes shaping the origin, structure, and evolution of our Universe. We need large cold apertures to reveal faint distant sources near the edge of the observable universe, and show us the details of even nearby warm sources with clarity that matches our capabilities for seeing hotter material.

2.2. Formation and Evolution of AGNs

It appears that central supermassive black holes are a nearly universal component of galactic bulges. Do the central black holes form first and serve as condensates for galaxies? Or do they build up as galaxies grow and merge? SAFIR will be a powerful tool to answer these questions. The low lying H_2 lines at 17 and 28.2μm are one of the few ways to study warm molecular gas condensations prior to the formation of metals, for example molecular gas around primordial massive black holes. Line widths and profiles will indicate whether the central mass is highly compact (suggesting a black hole), or if the molecular cloud is just in a mild state of turbulence. At the current epoch, galaxy mergers produce huge far-infrared fluxes through a combination of violent starbursts and AGNs associated with their central black holes. The distinction of starbursts from supermassive black holes as power sources for young and distant galaxies was identified in the Decade Report[1] as a major goal for new far-infrared telescopes.

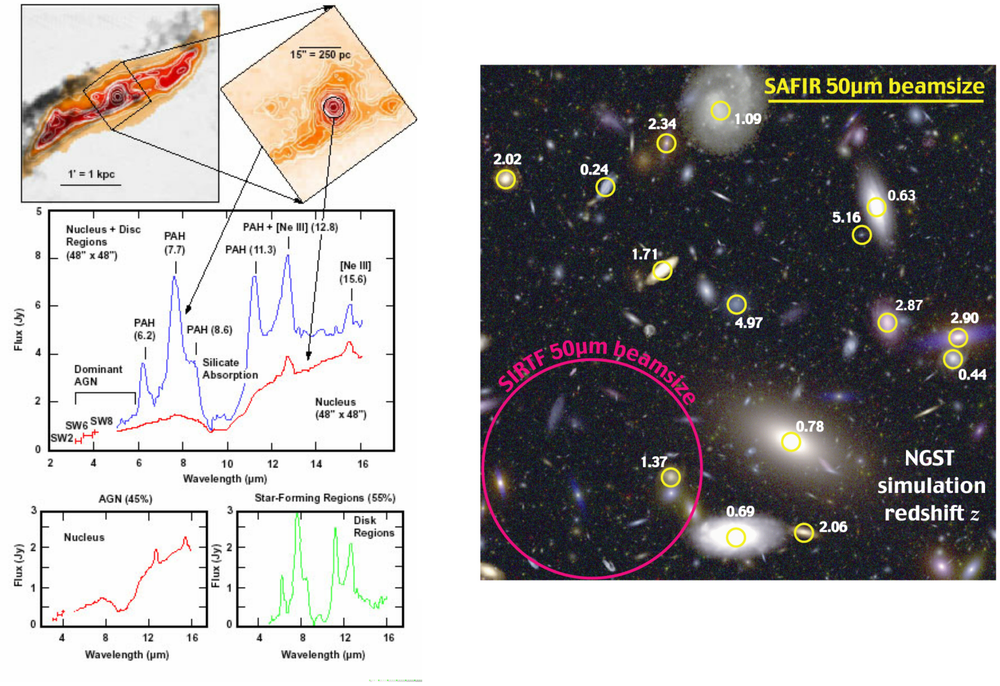

Figure 1. Left panel: The mid-IR spectrum of Centaurus A showing the wealth of spectroscopic features that will be shifted into the far-IR for young galaxies. Right panel: a simulation of an NGST field with galaxies marked at various redshifts, z. The SAFIR beamsize at 50μm is shown as well as SIRTF's, the most sensitive precursor mission.

What happens during the much more common mergers that build galaxies in the early Universe? COBE showed that the far-infrared-to-submillimeter energy density in the early Universe is comparable to that in the visible-to-near-infrared. What are the relative roles of dust-embedded AGNs and starbursts in producing this luminosity? Do AGNs at high redshift differ in basic properties from nearby ones? Models of the cosmic X-ray background indicate that the great majority of AGNs at high redshift are heavily absorbed.[5,6] Thus, these answers must be sought in the far-infrared where optical depths are low (interstellar medium, ISM, optical depths are similar at 20μm and 6 kev and rapidly decrease at longer infrared wavelengths and higher X-ray energies). The fine structure lines of NeII (12.8μm), NeIII (15.6μm) and NeV (14.3μm) are the best tool to distinguish unambiguously whether the ISM of a dusty galaxy is ionized by a starburst or by an AGN. Not only are the line ratios very well separated, but their extinction is reduced by more than a factor of thirty compared with the visible. At the epoch of peak quasar activity, these lines will be redshifted to the 45 to 55μm range. Figure 1 shows the spectrum of the nearby active galaxy, Centaurus A, illustrating the wealth of spectroscopic features that will be redshifted into the 25 - 100μm spectral region in early galaxies. Using these fine structure lines, a 10m far-infrared telescope will have the necessary resolution and sensitivity to determine the roles of star formation and nuclear activity in the early Universe. The full suite of infrared fine structure lines probes a very wide range of excitation energy, allowing SAFIR to constrain the UV spectra of AGNs and extending work done with ISO on a few nearby Seyfert galaxies to large lookback times. In addition, many of these lines have relatively high critical densities (up to $\sim 10^{10}$ cm^{-3}), so they have a unique ability to probe the density of the gas around AGNs. The angular resolution of SAFIR is a critical contribution to these studies, and complements that of forthcoming NASA investments in telescopes operating at shorter wavelengths. This capability is also illustrated in Figure 1 with a comparison of the SAFIR and SIRTF beams on a simulated NGST image.

2.3. Emergence of Stars and Galaxies

The history of star formation determines the evolution of galaxies and the generation rate of production of for heavy elements. It has been traced by deep Hubble Space Telescope (HST) imaging followed up with large ground-based telescopes. Even at modest redshifts, however, these techniques only probe the rest-frame ultraviolet. Here, SAFIR will make a critical contribution. Interstellar dust can absorb nearly all the UV in star-forming galaxies. In the best-studied starburst galaxies such as M82, a debate raged for more than a decade on how to correct even the near-infrared emission for interstellar extinction. Such corrections are poorly determined for galaxies at high redshift, so there are large uncertainties in the star-forming rate for z > 1 when most of the heavy elements were created. These uncertainties can be removed only by measuring the far-infrared emission from dust heated by young stars in these galaxies. The importance of this approach is underlined by the large cosmic far-infrared and submillimeter energy density discovered by COBE. This background has been partially resolved by ISO in the very far-infrared and is thought to arise from starburst galaxies at redshifts of up to z $\sim$ 3. SAFIR will resolve most of this high-redshift background into individual galaxies. This will allow us to image the dominant phases of dust embedded star formation and nuclear activity throughout the Universe. Since ultradeep optical images (e.g., Hubble Deep Field) reveal many galaxies too faint to contribute significantly to the submillimeter diffuse background, an entirely new population of optically faint, young galaxies must be responsible for it. A full understanding of star formation in the early Universe requires that we extend far-infrared and submillimeter measurements to these small systems. In this respect, SAFIR is crucial for understanding the processes by which primordial structure in the Universe leads to the first galaxies in it. In this luminosity range and over $1 < z < 5$, ALMA and other ground-based submillimeter telescopes are mostly sensitive to widespread and diffuse infrared cirrus emission which is thought to be the output of cold dust grains that are not necessarily heated by recent star formation. The rate of star formation in modest galaxies for $1 < z < 5$ can best be determined through high sensitivity imaging from 20 to 500μm.

In addition to reliable detection of a galaxy's infrared output, quantitative measurements of star formation require a reliable distance to it. Combining SAFIR and ALMA measurements of SEDs will give photometric redshift estimates, and SAFIR spectroscopy can measure redshifts directly using the strong PAH features in galaxy spectra near 8μm. In this way the sensitivity of SAFIR will allow us to measure galaxy luminosities to below L*, even out to z $\sim$ 5. Equally important is the resolution afforded by a 10m aperture; precursor far-infrared missions like SIRTF will be limited in this science objective by confusion noise.

2.4. Dynamical and Chemical Evolution of Galaxies and Stars

How do the first gas clouds form? What chemical processes occur within them and how do their characteristics change as the first traces of metals are injected into them by stellar processing? The capabilities of SAFIR are ideal for addressing these questions. Once even traces of metals have formed, the C+ line at 158μm becomes very bright. Its luminosity in nearby spiral galaxies is typically a few tenths of a percent of the entire bolometric luminosity of the galaxy. Although this line is marginally accessible in the poor atmospheric windows between 300 and 700μm, it can be routinely observed from the ground only at specific redshifts z > 4. The N^+ lines at 122 and 205μm also play important roles in cloud cooling. Study of the molecular hydrogen and these light metal fine structure emission lines in the early Universe and as a function of redshift promises to reveal many of the processes occurring in the gas clouds that build early galaxies. Space-borne observations in the far-infrared and submillimeter with an optimized observatory like SAFIR must be a major component of this study. The far-infrared fine structure lines also control the cooling of molecular clouds in the Milky Way. Understanding this process and related ones revealed by far-infrared spectroscopy is a key to advancing our knowledge of how these clouds begin their collapse into stars and planets (see below).

2.5. Birth of Stars and Planetary Systems

Stars are born in cold interstellar cloud cores that are so optically thick they are undetectable even in the mid-infrared. After 10^5 years, a young star emerges, ejecting material along powerful jets and still surrounded by a circumstellar disk. The subsequent evolution is increasingly well studied, but the birth of the star has occurred hidden from view. How does the cloud core collapse? How does subfragmentation occur to produce binary stars? What are the conditions within protoplanetary disks? When, where, and how frequently do these disks form planets? Imaging with the resolution provided by SAFIR ($<$ 100 AU at 40μm for the nearest star forming regions) can probe the density, dynamics, and temperature structure of these $\sim$1000 AU collapsing cores on critical physical scales. In addition, 100 AU resolution will reveal the steps toward binary formation. Far-infrared polarimetry is a powerful probe of magnetic field geometries, both for studying core collapse and mapping the fields that must play an important role in accelerating and collimating jets. Spectroscopy in molecular lines such as H_2O and the $J > 6$ high excitation rotational lines of CO, as well as in far-infrared atomic lines, can probe the physical and dynamical conditions in the collapse. Models of collapsing cloud cores[7] show that the [OI] lines have narrow components from the infalling envelope and broad ones from outflow shocks. They are the main coolant of the gas in the intermediate regions of the cloud. Bright H_2O lines between 25 and 180μm are the dominant coolant in the inner cloud, where a broad component is expected from the accretion shock and a narrow one from the disk. The CO lines from 170 to 520μm are the main coolant for the outer cloud; warmer CO from within the cloud can also be studied because of velocity shifts due to the collapse. This suite of lines therefore would allow us to probe thoroughly the kinematics and energetics process of star birth. The combination of angular resolution and sensitivity made possible with SAFIR is essential to these studies.

2.6. Evolution of Planetary Systems and the Origin of Life

What were the conditions in the early solar nebula, as the protoplanetary disk formed and planets and small bodies accreted out of it? All the bodies in the inner solar system have been so heavily processed that they no longer reflect the conditions at their formation. The discovery of many small bodies in the Kuiper Belt outside the orbit of Neptune gives access to objects where accretion proceeded slowly, leaving products that are primitive and still reflect conditions in the early solar nebula. There is a large population of Kuiper Belt Objects (KBOs), including objects of size rivaling the largest asteroids. They have a broad variety of surface characteristics. To interpret the clues they provide for evolution of the solar system requires that we understand how this variety of surface chemistry has come about. Two very important parameters are: 1) the albedoes of the surfaces (important to help identify the substances that cover them); and 2) surface temperatures (to understand what chemical reactions can occur and determine the escape rates for different molecules). Both of these parameters can be determined in the far-infrared through measurements of the thermal emission. It is for this reason that the 1998 National Academy of Sciences study on “Exploring the Trans-Neptunian Solar System” placed a very high priority both on large, far-infrared telescopes and on development of high performance far-infrared detector arrays, as are planned for SAFIR.

The Kuiper Belt is thought to be the source of short period comets and hence has a central role in the comet impacts that brought water to the earth and made life possible here. Most traces of this process, however, have been erased by time. How can we understand the conditions that regulated the early formation and evolution of the KB and its release of comets toward the inner solar system? The Infrared Astronomy Satellite (IRAS) discovered debris disks around Vega, β Pic, and other stars, with evidence for inner voids that might have resulted from planet formation. Many more will be discovered by SIRTF. The Kuiper Belt is similar in many ways to these systems and is interpreted as the debris disk of our solar system. Taking an example, β Pic is thought to be only about 20 million years old. Transient and variable absorptions by the [CaII] H and K lines in its spectrum have been interpreted as the infall of small bodies from the debris system.[8] This system contains small grains that heat sufficiently to be detected in the mid-infrared and scatter enough light to be seen at shorter wavelengths. Because it should be drawn into the star quickly, this fine dust must have been produced in recent collisions between planetesimals. Thus, this system and others like it demonstrate the potential of examining the early, violent evolution of debris disks and the infall of comets.

Debris disks are bright in the far-infrared, where they can be imaged to identify bright zones due to recent planetesimal collisions, as well as voids. The radial zones that are sampled will vary with wavelength, from a few AU near 20μm to hundreds of AU in the submillimeter. Figure 2 illustrates the potential advances with SAFIR. Spatially resolved spectroscopy can probe the mineralogy of the debris disks in the 20 - 35μm region where ISO has found a number of features diagnostic of crystalline and amorphous silicates, and can locate ice through its 63μm emission feature. Giant planets similar to Jupiter and Saturn could be detected to compare their placement with the debris disk structure. The latest community consensus for solar system astronomy from the National Research Council ("New Frontiers in the Solar System: An Integrated Exploration Strategy" – http://www.nap.edu/catalog/10432.html) identifies studies of the outer solar system and the Kuiper Belt debris disk as a top priority for mission development. In addition to analyzing the mission targets directly, SAFIR will complement this effort superbly by enabling comparative studies of debris disks around other stars.

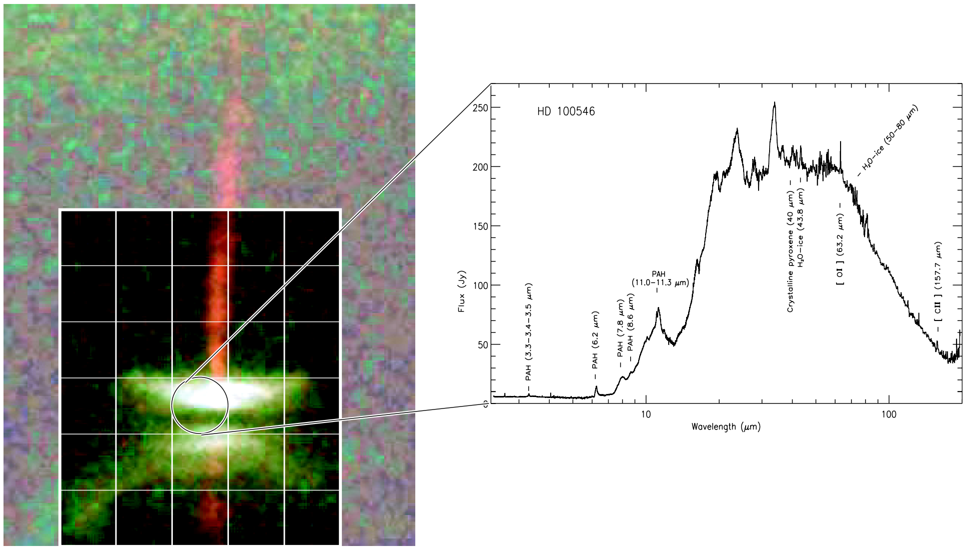

Figure 2. Illustration of the capability of SAFIR for studying debris around young stellar objects. The photo shows the disk of HH30 as seen by Hubble, with the field of view of a SAFIR image slicing spectrometer superimposed. The spectrum highlights the rich spectral information present in such objects - in this case, HD100546 as seen by ISO. SAFIR will be able to detect features in such debris disks as far away as the Galactic center.

2.7. Discovery of New Phenomena

Technological advances enable astronomical discoveries. Harwit tried to quantify this relation in "Cosmic Discovery."[9] In the 25 years preceding publication of the book, important discoveries were made within 5 years of the development of new technology that made them possible. The exceptional discovery potential in the far-infrared/sub-millimeter region arises because the sensors are still substantially short of fundamental performance limits and the telescopes available to date have been very modest in aperture (less than 1 meter!). The previous decadal survey developed a parameter to describe the discovery potential of new missions, which they called astronomical capability. This parameter is proportional to the time required to obtain a given number of image elements to a given sensitivity limit. SAFIR will have astronomical capability exceeding that of past far-infrared facilities by a factor of about 10^{10}, and will still offer a gain of about 10^5 after SIRTF and Herschel have flown. A gain of 10^5 is similar to the gain from the initial use of the Hooker 100-Inch Telescope on Mt. Wilson to the Hubble Space Telescope. While the capabilities of SAFIR will enable enormous progress on some of the most important problems in modern astronomy, this huge gain in discovery capability is certain to lead in new and exciting directions as well.

3. TELESCOPE AND INSTRUMENT REQUIREMENTS

Table 1 summarizes the requirements on the SAFIR telescope and the science driving each of them.

Table 1 - Telescope Requirements For SAFIR

Parameter	Requirement	Driving Science
Aperture	> 8m	Dusty Galaxies at $z = 5$; Resolve Debris Disks
Optics Temperature	~ 4K	Spectroscopy; detecting L^* Galaxy at $z \sim 5$
Wavelength Range	20 - 800μm	NGST Overlap; Gas Cooling Lines;
Diffraction Limit	40μm	Imaging Debris Disks, Distant Galaxies
Pointing Accuracy	$\sim$ 0.5 - 1.0"	Driven by 40μmDiffraction Limit
Pointing Stability	$\sim$ 0.1"	Driven by 40μmDiffraction Limit
Lifetime	> 5 Years	Overall Productivity

The two most critical requirements are aperture and operating temperature, assuming the emissivity is minimized to a level limited by optical coatings and reasonable stray light considerations. The aperture and telescope background emission determine its ultimate limiting senstivity as well as the practical limit of the number of seconds of integration required to reach the confusion limit on the sky. The science drivers for SAFIR require the confusion noise to be low enough to observe typical dusty L^* galaxy formation close to the epoch of metal enrichment, $z > 5$. Another important driver is the ability to study the formation and evolution of planetary systems via their debris disks out to distances, $D \sim 100$pc. These requirements imply an aperture of order 10m for SAFIR. Figure 3 shows an estimate of the confusion limit for an 10m aperture telescope[10] as a function of wavelength relative to the photon background limited sensitivity for an assumed 5% emissive telescope of various possible temperatures and for two representative integration times, 1 and 10^4 seconds. To reach a confusion limit comparable to the brightness of L^* galaxies at $z \sim 5$ at 100μm requires $T \leq 10$K. For spectroscopic purposes, however, the confusion limit is much lower and it is therefore important that the telescope be even colder, 4K, to detect lines from distant galaxies.

The next most critical requirement is on the short wavelength limit for SAFIR since this drives the optical surface and alignment tolerances and thus, the technology chosen for the primary mirror. In order to provide high sensitivity and angular resolution for complete coverage of the very wide range of wavelengths in the infrared, it is essential that SAFIR's wavelength coverage extend down to overlap with NGST's at $\lambda \sim 20\mu$m. The science drivers described above require diffraction-limited peformance at a somewhat more relaxed wavelength limit of 40μm for imaging of debris disks and distant galaxies. The diffraction limit at 40μm for a 10m telescope is $R \sim$ 1" (1.2 λ/D). Therefore, the requirements on pointing accuracy and stability ($\sim$ 0.5 -1" and 0.1" respectively), as well as surface quality for SAFIR will be relatively modest in comparison with NGST. Thus the NGST engineering R&D can be assumed to carry over at some level to SAFIR. In the post-NGST era, the biggest technological challenge is likely to be the required telescope temperature.

The science program that motivates the need for SAFIR requires a complement of imaging and spectroscopic instruments over the entire wavelength range of SAFIR from 20 - 600μm. Table 2 lists a strawman complement of instruments along with some of the science drivers from §2.

Table 2 - Strawman Instrument Complement For SAFIR

Instrument	λ Range	Spectral Res.	FOV	Driving Science
Camera	20 - 600μm	$\sim$5	1-4'	High Z Reddenning; KBO's; ...
Spectrometer	20 - 100μm	$\sim$100	$\sim$10" (Image Slicing)	Debris Disks, YSO's
Spectrometer	20 - 800μm	$\sim$2000	$\sim$1'	C^+, N^+; Chem. Evolution
Spectrometer	25 - 520μm	$\sim 10^5$	$>$1 beam	Dynamics; Gas Cooling

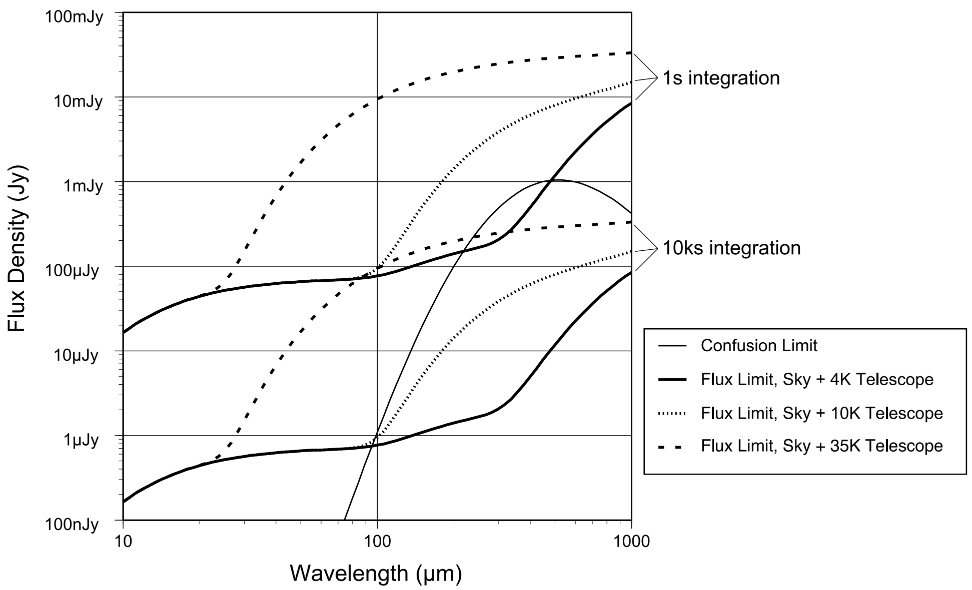

Figure 3. SAFIR sensitivity as a function of telescope temperature and integration time, as compared to the confusion limit.

Figure 4 displays the sensitivity of SAFIR relative to a number of precursor missions as well as several that are hoped to follow it. Also shown is the angular resolution of SAFIR as a function of wavelength in the context of existing, planned, and possible future missions. It is clear from these figures that SAFIR not only offers a dramatic increase in sensitivity over precursor missions, but provides a bridge in sensitivity between the most powerful telescope at shorter wavelengths (NGST), and that at longer wavelengths (ALMA).

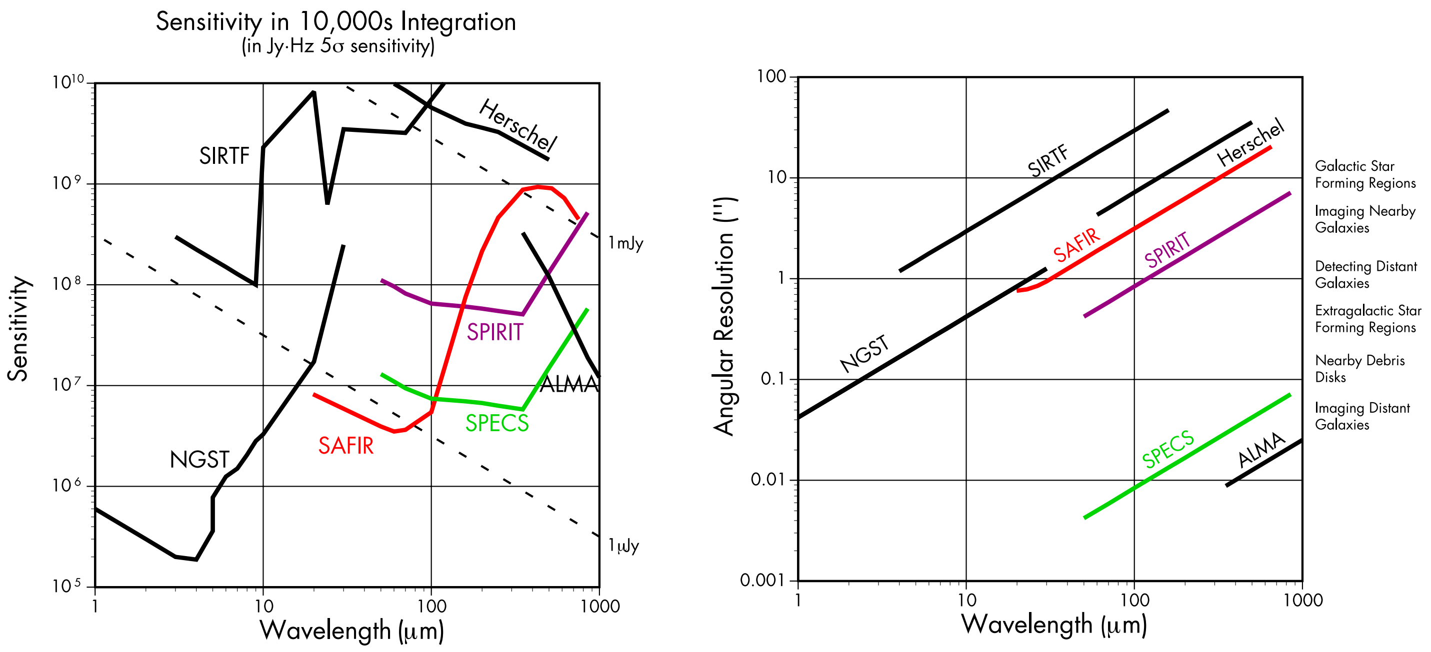

Figure 4. SAFIR sensitivity compared to present and future mission concepts.

4. TELESCOPE CONCEPTS AND EXPECTED PERFORMANCE

Figures 5 and 6 show two possible concepts for SAFIR that are under study. The first, which has been studied by NASA’s Goddard Space Flight Center, is based on the National Academy’s recommendation: “To take the next step in exploring [the far-infrared], the committee recommends the SAFIR Observatory, a. . . telescope that builds on the technology developed for NGST.”.[1] Taking NGST’s current designs as a starting point, a detailed analysis was made of the changes necessary to produce a SAFIR that is implemented as a larger, colder version of NGST.[11] A broad list of science investigations was used to generate an explicit list of technology requirements, from which the observatory requirements (§3) are derived.

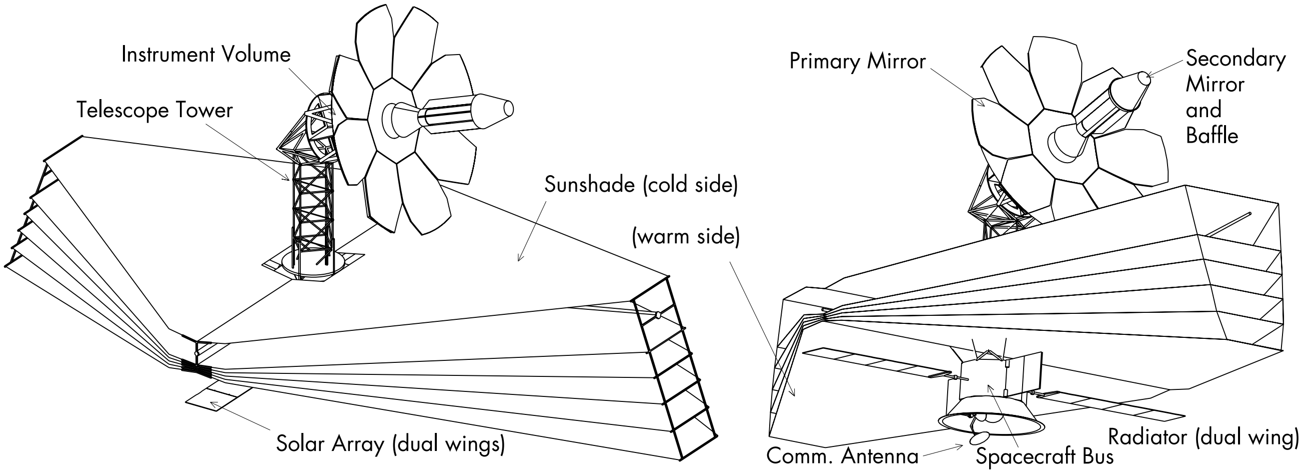

Figure 5. SAFIR concept under study at NASA-GSFC, based on heritage from NGST.

One of the immediate differences between SAFIR and NGST is that, in order to achieve the ultimate sensitivity for the difficult spectroscopic observations planned for SAFIR, the telescope and other optics will have to be cooled to 4K, well below the $\sim$35K achieved by NGST’s passively-cooled architecture. GSFC’s conceptual design for SAFIR uses a cascaded cryocooler to provide moderate cooling powers at 40K, 15K, and 4K. The NGST-like sunshade is mounted on the 40K stage, while a single additional layer of the sunshade is mounted on the 15K stage. This sunshade will provide an environment so well shielded from the Sun that only modest cooling is needed to bring the telescope down to 4K.

There are currently two methods of deploying a large, rigid primary mirror for NGST: petal-like folding or drop-leaf-table-like folding. The GSFC SAFIR design will reproduce NGST’s approach following NGST’s selection of a primary contractor. Since SAFIR is larger than NGST, the designs will diverge somewhat: a petal design will result in small notches around the outside of the aperture, while a table-fold design will have two small slices off the aperture edges. The PSF will be slightly degraded, but the collecting area at large radii will still benefit confusion-limited and sensitivity-limited observations. The choice of optical surface is largely independent of the method of deployment and can be deferred until NGST has validated its technology. Among the competitors for SAFIR are carbon fiber mirrors and structure (probably with glass face-sheets), C/SiC mirrors and structure, beryllium, and aluminum mirrors. Given that SAFIR does not require diffraction-limited performance at $\lambda < 40\mu$m, it might be possible to duplicate the NGST mirror technology, but without the final polishing process. It is also possible that the telescope could use a non-NGST-like optical design, as discussed below.

In order to fit the four strawman instruments described in §3, a large field of view ($\sim$15’ diameter) is needed. Because the diffraction-limited resolution at the shortest wavelengths is $\simeq$1”, a pointing stability of 0.1” is desirable. This can be achieved only with a cryogenic pointing camera located on the instrument package. GSFC’s concept uses a 2μm focal plane camera with a large field of view and high speed subarray readout in order to measure jitter offsets from known 2MASS point sources.

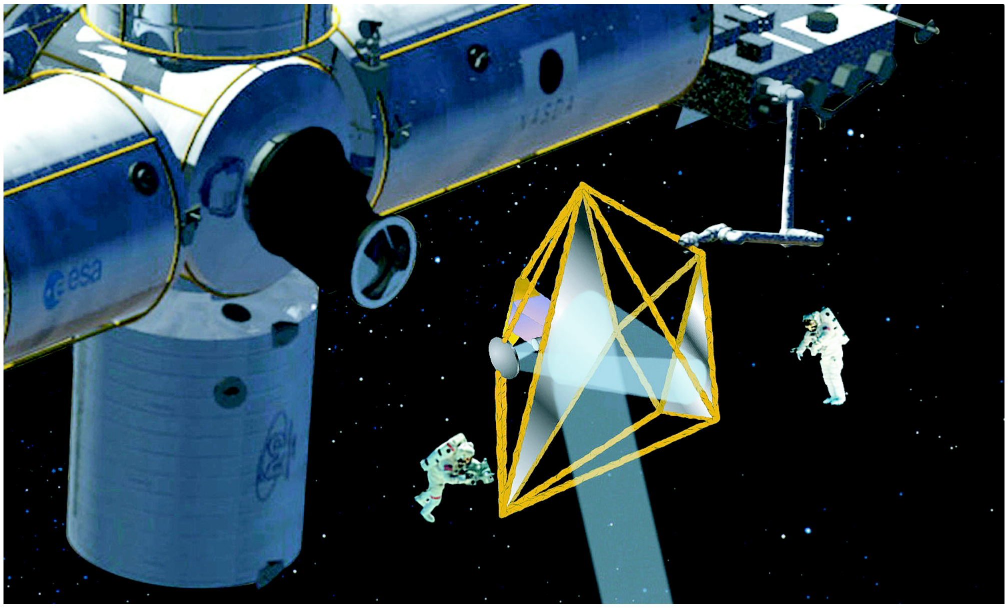

Figure 6. DART concept under study at NASA-JPL and Lockheed-Martin (figure from LMMC). In this image, a ∼ 1.5m DART prototype is being assembled by astronauts at the ISS. A SAFIR implementation of DART would be much larger, and would feature a sunshield and spacecraft suitable to cooling and moving the truss structure.

The GSFC mission concept requires that SAFIR be launched by a Delta-IV Heavy in order to provide a large fairing volume for the stowed observatory. Although SAFIR is a massive observatory, it is well beneath margins available from this launch vehicle. Mission operations would be conducted similarly to the NGST operations. With the concept outlined above, SAFIR could be launched shortly after NGST in around 2015.

The second concept has undertaken to break the paradigm of launching large, often massive mirrors into space. Instead, NASA's Jet Propulsion Laboratory has been developing a concept using membrane mirrors tensioned by truss structures assembled by astronauts. Called the Dual Anamorphic Reflector Telescope (DART) system, this telescope consists of two parabolic-cylindrical trough-shaped reflectors oriented with respect to each other to produce a point focus (figure 6). Since each reflector contains only a single simple curve, the mirrors can be formed by tensioning a reflective foil over a frame with a parabolic contour along one axis. The use of an extremely low-mass membrane for the reflective surfaces would significantly reduce the mass of the telescope. In traditional telescope architectures, the larger the aperture desired, the greater the mass required for the optics support structure. The DART architecture uses a thin membrane for its reflectors, so the density of the mirror surface is independent of size. In fact the ratio of structure to reflector mass can decrease with increasing aperture size. Historically, a lower mass telescope will have a lower mission cost; if the telescope dominates the mass of the SAFIR observatory, the membrane mirror will be an important technology to consider. If the problems of deploying and cooling a membrane mirror can be solved, and the field of view and surface figure made adequate, this technology might be a viable replacement for the NGST mirror in a SAFIR concept.

5. PROJECT STATUS

With the imminent selection of the NGST prime contractor, it is timely to begin mission concept studies for SAFIR. The development of the NGST telescope may result in approaches that can be readily adapted to the far-infrared, with the differing requirements of (1) colder operating temperature; (2) relaxed image quality; and (3) larger aperture. These three important differences, however, may lead to unique architectures for the far-infrared telescope. Investment in the development of the various design concepts is a critical need in the near term. This basic decision must be made as soon as possible to guide further development of the mission.

Although autonomous deployment is a possibility, opportunities for reduced cost and risk through in-space assembly can also be explored.

5.1. Detector Technology

The far infrared and submillimeter ranges have benefited relatively little from investments in detector technology by non-astronomical pursuits. In this regard, they differ dramatically from the visible, near- and mid-infrared, and radio regions. Detectors in those spectral regions closely approach theoretical performance limits. In the far-infrared the investment in technology to date has been modest, due both to technological hurdles in using the technology which have now largely disappeared, and to the lack of direct applications in the defense industry. This much smaller prior investment has left the possibility for orders of magnitude further progress toward fundamental limits. Figure 7 illustrates the three major detector technologies. Each has current strengths and weaknesses. Far-infrared photoconductors are the most advanced in array construction, as shown by the space qualified SIRTF array in the figure, and require relatively modest cooling. They fall somewhat short of theoretical limits in potential performance, however, and respond only up to the excitation energy. Development should address larger arrays, at least 128x128. Bolometers have broad spectral response and are the most advanced submillimeter continuum detectors, but they require extremely low operating temperatures. Development needs to emphasize improved array technology, such as SQUID-based multiplexing, and superconducting-thermometer bolometers that interface well to SQUID electronics. Hot electron bolometer mixers provide the best heterodyne operation above the superconducting gap frequency of NbTiN, around 1200 GHz. They can have large advantages for spectroscopy over photoconductors and bolometers. Development needs to address reducing noise temperatures and developing support electronics to allow large scale spatial arrays.

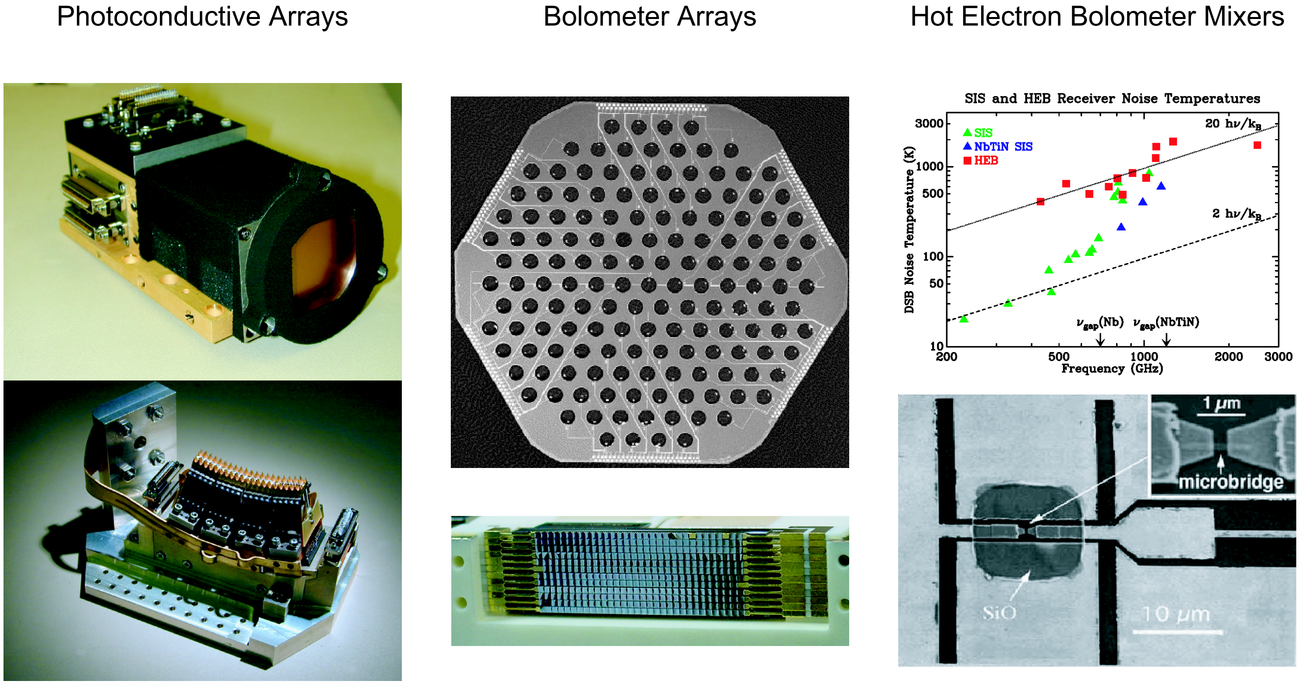

Figure 7. Suitable detector technologies for SAFIR, representing current state-of-the-art but not yet sufficient to SAFIR's requirements.

5.2. Budget

Goddard Space Flight Center estimated the budget for SAFIR for the UVOIR panel of the Decadal Survey as \$310M for construction, \$85M for launch, and \$100M for 5 years of operations. They drew on their experience estimating the cost of NGST, so the relative comparison of the two missions is also meaningful. They assumed that no additional development would be required beyond that for NGST, although the report indicated that this was probably not entirely correct. A significant development program, perhaps even departing significantly from the NGST telescope architecture is likely to be half that for NGST, or an additional $125M, for a total cost of $620M. For comparison, the estimate of the UVOIR panel for NGST was $1114M. The decadal survey committee also recommended a budget over the decade for the technology development that would support SAFIR and other projects in the far-infrared and submillimeter of $140M, including $10M for detectors, $50M for space refrigerators, and $80M for large, lightweight optics.

6. SUMMARY

With a start near the end of the decade, SAFIR follows several missions that will lay its scientific and technological foundation. SIRTF, whose mission will be complete by the time SAFIR would go to Phase B definition, will leave a Great Observatory legacy of mid- and far-infrared observations along with the technical demonstration to make a large cold telescope a compelling next generation facility. SOFIA will have operated for a number of years, providing both a testbed for detector technology and a high level of flexibility and accessibility in its explorations of the far-infrared sky. Herschel will be completing its examination of the submillimeter range, both for continuum sources and with powerful spectroscopic instrumentation. None of these missions, though, will approach the potential for this spectral range, SIRTF because of its small aperture (85cm) and SOFIA and Herschel because of the thermal background due to their relatively high operating temperatures ($\sim$ 220K and $\sim$80K respectively). SAFIR is well within reach technically, given the modest requirements on its optics and pointing, the infrastructure under development within NASA for large telescopes and large satellites in general, and the potential for dramatic advances in detector technology at modest cost. SAFIR will lay the foundation for the next steps in exploring this spectral region, such as the SPECS space-borne interferometer. NGST and ALMA will begin operation toward the end of the decade. The timely arrival of SAFIR to bridge the spectral gap between them will complement the capabilities of both facilities, maximizing the productivity of two other major investments in astronomical capability.

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