Thermal design trades for SAFIR architecture concepts

Harold W. Yorke[a], Christopher Paine[a], Matt Bradford[a], Mark Dragovan[a],
Al Nash[a], Jennifer Dooley[a], Charles Lawrence[a]
[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

ABSTRACT

SAFIR is a 10-meter, 4 K space telescope optimized for wavelengths between 20 microns and 1 mm. The combination of aperture diameter and telescope temperature will provide a raw sensitivity improvement of more than a factor of 1000 over presently-planned missions. The sensitivity will be comparable to that of the JWST and ALMA, but at the critical far-IR wavelengths where much of the universe's radiative energy has emerged since the origin of stars and galaxies. We examine several of the critical technologies for SAFIR which enable the large cold aperture, and present results of studies examining the telescope optics and the spacecraft thermal architecture. Both the method by which the aperture is filled, and the overall optical design for the telescope can impact the potential scientific return of SAFIR. Thermal architecture that goes far beyond the sunshades developed for the James Webb Space Telescope will be necessary to achieve the desired sensitivity of SAFIR. By combining active and passive cooling at critical points within the observatory, a significant reduction of the required level of active cooling can be obtained.

Keywords: SAFIR, thermal control, infrared telescopes, submillimeter telescopes

1. INTRODUCTION

In their decadal report, *Astronomy and Astrophysics in the New Millennium*, the Astronomy and Astrophysics Survey Committee recommended an initiative for a Single Aperture Far Infrared Observatory (SAFIR). SAFIR is envisioned as a 10 meter, 4 K space telescope operating in the wavelength regime from 20 μm to about 1 mm, and the large cold aperture will make the mission far more sensitive at overlapping wavelengths than any existing or planned facility, including the Spitzer Space Telescope (SST), the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the Herschel Space Observatory. Indeed, SAFIR's combination of a large cold aperture with state-of-the art instrumentation provides the potential for 3 to 5 orders of magnitude improvement in sensitivity relative to its predecessors!

Critical to SAFIR's success in achieving these goals is the large cold aperture, and studies are underway examining two principle technologies: the telescope optics and the spacecraft thermal architecture. Both the method by which the aperture is filled and the overall optical design for the telescope strongly impact the potential scientific return of SAFIR. A thermal architecture that goes beyond the sunshades developed for the James Webb Space Telescope will be necessary to achieve the desired sensitivity of SAFIR. Investigations into the limits of passive cooling hold the promise of eliminating excessive reliance on active coolers. Particular combinations of passive cooling and active heat intercepts at well chosen locations will significantly reduce the requirements for and constraints on deployed active cooling systems.

2. SCIENTIFIC MOTIVATION

SAFIR's tremendous capability will enable breakthrough studies of astrophysical process over a wide range of topics. While it is difficult to predict the most important scientific advances enabled by a mission 15 years in the future with a 1000- to 10000-fold increase in capability (see Fig. 1), we highlight some of the most obvious scientific applications of SAFIR within our current scientific framework. For a more complete discussion we refer the interested reader to the paper by Lester et al. (2004) in this volume.

A) *The epoch of reionization (z~10-20) when the first stars collapsed from pristine material, ignited their nuclear fires, and enriched the universe with heavy elements.* Because of the lack of heavy elements in the primordial gas, the collapse and formation of the first stars occurred at higher temperatures, and larger masses than for star formation in the present day. Models suggest that these collapsing objects could be detectable with SAFIR in the lowest molecular hydrogen rotational transitions, redshifted from their rest-frame mid-IR wavelengths to the submillimeter. The supernova remnants from these objects might also be detectable as they radiate much of the energy in shock cooling lines.

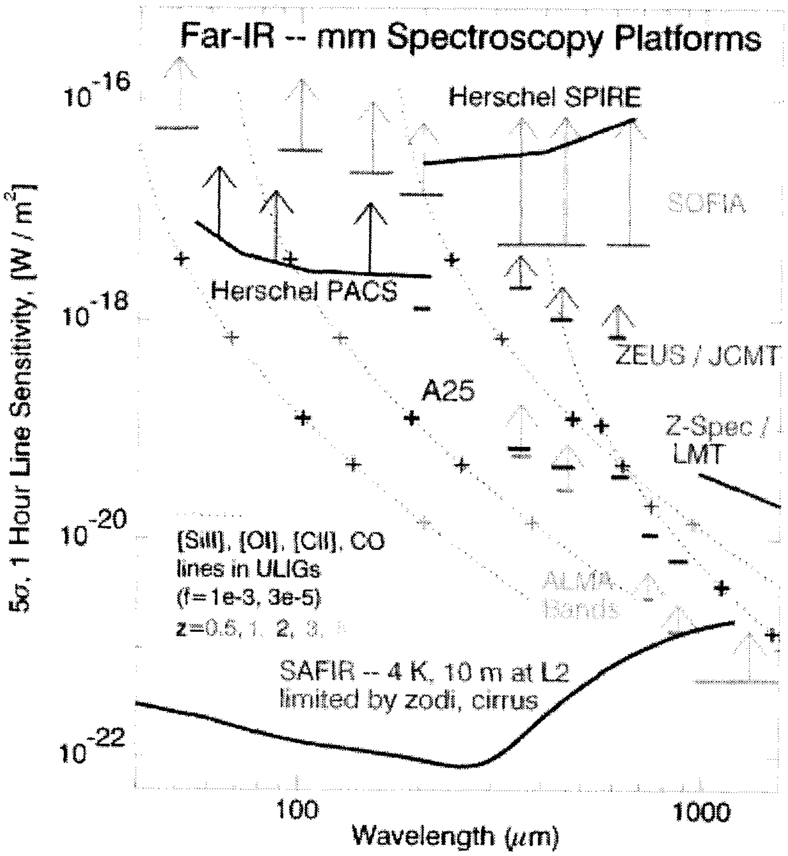

Fig. 1. Sensitivities of far-IR – mm-wave spectroscopy platforms. SAFIR's large cold aperture offers huge gains over the planned and existing facilities, e.g. Herschel, SOFIA, ground-based platforms primarily because of their warm (relative to SAFIR) temperatures. Sensitivities are taken from the instrument web pages, the calculations for SAFIR assume regions of low zodi and cirrus, and assume 25% total coupling to the detectors, as might be achieved with a carefully designed grating spectrometer with bolometers. Upward arrows indicate the effective sensitivity for surveying a 40% bandwidth, instruments with small instantaneous bandwidth incur a time penalty.

B) *The chemical evolution of the universe since reionization: the history of energy release and metal production in galaxies since their inception.* Recent results indicate that the star formation rate was an order of magnitude greater at redshifts 1 to 5 than in the present day, presumably as galaxies assembled and formed the bulk of their stellar populations. About half of the energy released over the ages is obscured optically and emerges in the far-IR, demonstrating the importance of dust, and far-IR measurements. At the long wavelengths in the continuum, source confusion is an issue, and SAFIR's 10 meter aperture offers a beam 3 times smaller (10 times smaller solid angle) than that of Herschel. According to current models of source counts, this smaller beam will allow SAFIR to extract sources 10-1000 times fainter than will be possible with Herschel, and will resolve the bulk of the cosmic IR background into its sources for $\lambda<100$ •m. For spectroscopy, there is no confusion limit, and as the curves in Fig. 1 show, spectrometers will probe galaxies at redshifts beyond 5, detecting lines which measure the mass and physical conditions in the galaxies without extinction biases. These measurements over a large sample of high-redshift galaxies chart the cosmic history of nucleosynthesis and energy production.

C) *The processes at work in galactic nuclei: the relationship between massive black holes and the material in their host galaxies.* Sensitive far-IR spectroscopy with SAFIR will allow rapid surveys of hundreds Seyfert nuclei. If our current understanding is correct, each spectrum will reveal simultaneously the far-IR rotational lines of H_20 and CO from the T~1000 K molecular torus, and the high-ionization atomic fine structure lines from the gas near the nucleus itself – a complete census of the material associated with accretion. These measurements on a large sample will constrain our models of active galactic nuclei.

D) *Detailed studies of "local" star and planet formation: star forming regions, protostellar and debris disks.* The earliest phases of star formation are highly obscured by dust; studies of stars in their infancy thus require wavelengths at the mid-IR and longer. Because young, low mass protostellar systems (i.e. solar system analogs) have typical size scales of 100 AU and luminosities measured in a few solar luminosities, their typical temperatures are ~100 K. The mid- and far-IR is thus the natural spectral regime for studying these types of objects. The formation of massive stars plays a crucial role in the evolution of galaxies and, here again, our understanding of the earliest phases is hampered by our lack of high quality data in SAFIR's wavelength range. Sensitive multi-wavelength far-IR continuum imaging measures the mass and temperature distribution of the dust as well as the grain properties. Spectroscopy of atomic and molecular species probes the mass, temperature and density of the gas. Spitzer's studies will revolutionize our understanding of these objects with detailed studies of nearby sources, but SAFIR will enable sensitive study of hundreds to thousands of low mass protostellar and debris-disk sources and hundreds of high mass protostars in our Galaxy (and in galaxies of the Local Group), revealing an evolutionary sequence and constraining our models of star and planet formation.

3. OPTICAL DESIGN CONSIDERATIONS

The optical design and architecture of the telescope system are critical to SAFIR in achieving the science goals. A number of designs for two and three mirror systems have been developed, resulting in systems that have large focal surfaces (Schroeder 1987). The systems described are generally on-axis, where the secondary and tertiary optics obstruct the primary reflector. Scattering and diffraction of the incident electromagnetic radiation by the secondary optics and its support structure reduces the performance of the overall system. This is problematic for observations of low-contrast objects, like the ones to be observed with SAFIR.

The solution is to use an unobstructed, off-axis design. Unfortunately, the field-of-view of such a system can be limited unless steps are taken to control the new set of off-axis aberrations. A solution using confocal conic reflectors was devised by Dragone (1982). Other designs, such as the aplanatic Gregorian or the Schwarzschild (1905; Claydon 1975) solution have lower distortion and provide a wider field-of-view for off-axis systems at the expense of greater complexity of the surface shapes.

The telescope needed is one that has an unobstructed aperture, and a continuous reflecting surface, ie does not have segments with gaps. Three possibilities present themselves. 1) a monolithic off-axis reflector. 2) A segmented reflector assembled with no gaps between adjacent elements. 3) A new design employing 2 tensioned membrane reflectors to produce a single focus (see Fig. 2).

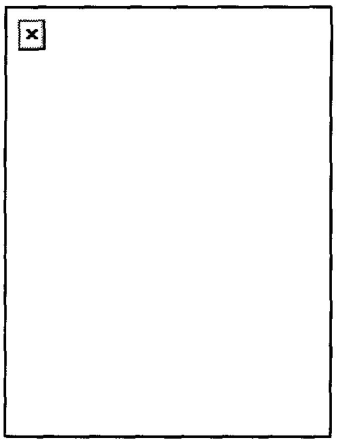

Fig. 2. The NGST off-axis design and the layout of the DART optical arrangement. With an off-axis, unobstructed aperture telescope design the fundamental limitation to the performance will be the intrinsic roughness of the reflecting surfaces. The resultant beam patterns are then determined by the edge illuminations of the reflectors in the system. The ultimate choice of telescope design and architecture will be an optimization between cost and performance.

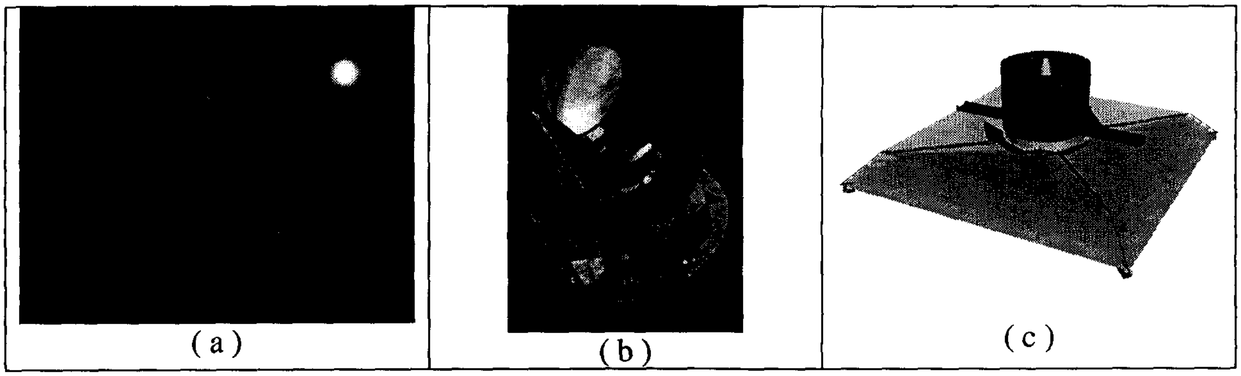

Fig. 3. Optimal extension of the passive cooling developments of the (a) Spitzer Space Telescope, (b) Planck and the (c) Terrestrial Planet Finder can enable SAFIR's required performance without excessive reliance on active coolers.

4. THERMAL DESIGN

4.1 Telescope materials and thermal performance

Several fairly recent developments in mirror technology appear to offer promise of lower areal mass without compromising optical performance, while being compatible with the thermal requirements of operation at or near 4 K. This is far from an exhaustive survey; included are some materials with areal density 4 times larger than desired but with flight heritage, and some which offer promise but have not been tested cryogenically.

4.1.1 Considerations for thermal performance of mirror materials

As shown in Fig. 4 and discussed later, we assume a thermal-mechanical structure in which the telescope support is actively cooled to the temperature of the reflector elements at a point between the final shield and the attachment to the telescope. In this case, the primary heat input to the telescope elements is thermal radiation, from the coldest shield (~15-20 K) and the zodiacal background. Mechanical actuators are either inoperative during observing, or are separately heat sunk. The instrument package is cooled to the same temperature as the telescope. The individual telescope reflector elements are poorly coupled thermally to each other, to allow mechanical motion for optical alignment. The temperature profile of each reflector element is then determined by the radiative power input density, the conductance of the element and its support structure, and the configuration of heat sinks.

Care must be taken to properly include the thermal contribution of the zodiacal background as a source of thermal power into the mirror elements. Although the total radiant power in the zodiac background is equivalent to that from a blackbody at 5 to 7 K, the spectral content has peaks at ~0.5 um and ~13 um, corresponding to back-scattered solar light and emission from diffuse dust. The Hagen-Rubens form for bulk metal emissivity indicates that absorption of the zodiacal light can be up to 36 times that which would be expected at ~600 um, the peak of the equivalent-power blackbody spectrum. Depending upon the solid angle subtended by the cold shields, the zodiacal light could rival thermal emission from the shields as a thermal input to the telescope.

Both the spatial and temporal uniformity of telescope temperature is important in obtaining highest sensitivity from the instruments. Long-wavelength bolometers are usually fabricated to exhibit optimal sensitivity within a narrow range of illumination, so viewing different areas of a reflective surface can yield different background illumination if thermal gradients exist across the surface; this can degrade detector sensitivity. Similarly, time variation in the mirror temperature may render detector output difficult to interpret. Small spatial gradients, and rapid equilibration after repointing, are thus desirable characteristics. The former can be achieved by large lateral conductance of the reflector element to one or a few heat sink points, or by distributing the heat lift over a larger number of closely-spaced points.

4.1.2 Preliminary thermal modeling results

Thermal modeling of some candidate reflector materials suggests that acceptable (few percent) thermal gradients can be achieved with heat sink locations at separations of 1-2 meters for individual telescope elements. In the examples following, we have assumed a conservative 0.03 average emissivity over the wavelength range of importance for thermal effects (approximately 1 to 200 μm), for both the telescope and final shield, a final shield temperature of 20 K, and a field-of-view of the shield from the telescope of 0.2π sr. The telescope element temperature is 4 K.

The DART reflector pair, consisting of tensioned single layers of 0.05 mm copper foil with no backing structure, have slightly greater than 1% thermal gradient across a 10 m width if opposite edges are maintained at fixed temperature. The thermal mass is small, so equilibration after repointing is rapid, probably a matter of minutes. Areal mass will be dominated by the support and figuring structure, and is estimated to be 5 kg/m^2 for a 10 meter aperture.

Composite Optics Incorporated has demonstrated a 25 cm diameter mirror with POCO carbon foam core and epoxy-bonded carbon-composite face sheets. Areal density is ~12 kg/m^2. Reflectivity and final figuring are achieved with electro-deposition of copper, followed by diamond-machining resulting in surface figure better than 1 nm (rms). The pre-machining copper thickness is 0.076 mm; thermal contact over perhaps 0.1 of the circumference of such a reflector would reduce thermal gradients to below 1% for 1 m class elements, but this might interfere with the optical performance unless the contact can be achieved inside the core. Alternatively, the thermal conductance of the graphite foam core may be large enough to allow cooling at the back surface, which is also copper coated. The foam has excellent thermal properties at room temperature, but to the best of our knowledge, this mirror has not been tested at cryogenic temperatures. The conditions under which closeout is performed may also affect mirror figure processing; if the foam core is sealed with gas pressure inside, the figure may change as the external pressure vanishes, which would complicate figuring.

Schafer Corporation has demonstrated foam-core encapsulated Si and SiC mirror elements to temperatures as low as 27 K, for high-energy laser applications; different surface coatings would be required for SAFIR. The thermal properties of the Si and SiC core appear to be adequate for single-point heat sinking. Areal density of these mirrors is ~10 kg/m^2, with production diameters of 0.6 m expected soon or currently available.

Beryllium is of course a thermally attractive material, as it is uniform, of thermal conductance comparable to aluminum alloys, and fabricated in fairly thick cross-section. SIRTF and other applications have demonstrated repeatable thermal cycle behavior to the temperature range of SAFIR. Making thermal contact is expected to be straightforward, and at the power densities of interest, a single heat sink anywhere on the element will produce the required temperature and uniformity. However, the areal density of beryllium mirror elements is unlikely to be less than ~25 kg/m^2, more if a more complicated deployment mechanism is required. Silicon Carbide has similar characteristics but somewhat higher density (~31 kg/m^2). Both will have extensive flight heritage (Herschel, JWST) by the time SAFIR flies.

Continued evaluation of mirror materials and demonstration of heat lift and acceptable thermal profile from candidate mirror materials are activities planned or proposed for ongoing JPL efforts.

4.2 Thermal design considerations

4.2.1 Passively cooled radiation shields with active heat interception from support structure

Thermal radiation from the coldest shield imposes thermal loads on the telescope and structure, and is a source of stray light scattered into the focal plane by imperfections on the mirror and potentially by the structure. Analysis indicates that a final shield temperature of 20 K, or possibly as high as 25 K, may be adequate for thermal reasons; however, stray light limits may require that temperature be as low as 15 K. The shield design applied for JWST is adequate for that mission, but much better shielding must be implemented for SAFIR. JPL is undertaking analysis to determine what thermal environment can reasonably be achieved using multi-stage passive radiation shielding coupled with active heat intercept between the warm spacecraft bus, the shields, and the telescope support structure. Fig. 4 shows the general approach taken in the parametric study, indicating options for active heat lift from the structure and passive cooling of the shield surfaces. This analysis is not sufficiently mature to report final results, but experience with high-performance passive radiators suggests that a 15 K environment at the final thermal shield is attainable in a deployable configuration. The shield temperatures given in Fig. 4 are the results of an analysis of a purely passive system (no active heat lift at any points) for a 4 to 6 m class telescope in the DART geometry; the shield total diameter is 20 m, which is a reasonable approach to what will be required for SAFIR. The final shield temperature in this configuration is 16 K without active heat lift from the support structure. These early results, while overly optimistic when considered with the demonstrated performance of Spitzer shields and the current estimates of <45 K for three passive shields on Planck, strongly indicate that passive radiative shields can attain 15 K, especially when coupled with active heat interception in the structure.

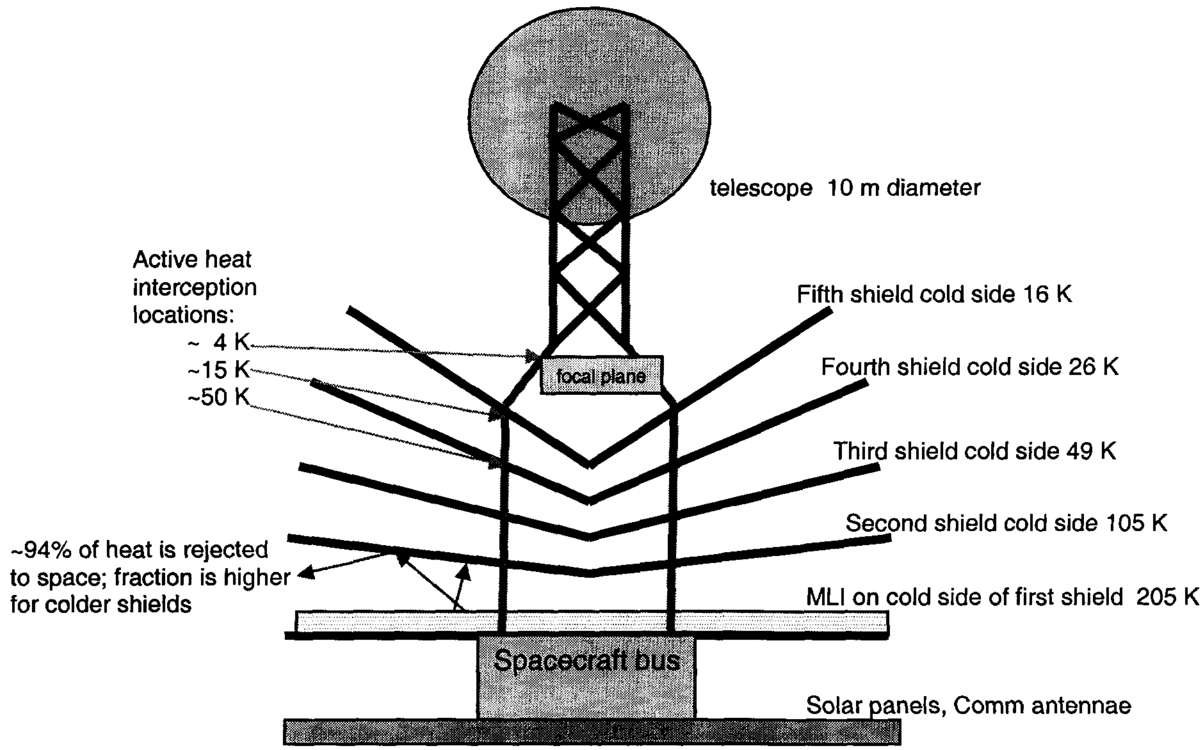

Fig. 4. Schematic of architecture for trade study: Low-conductance support structure between spacecraft bus and telescope, with active heat interception as required to reduce heat into passive radiators. Focal plane and telescope structure is cooled to 4 K above final radiation shield. Temperatures shown are for a similar structure, as is discussed in the text.

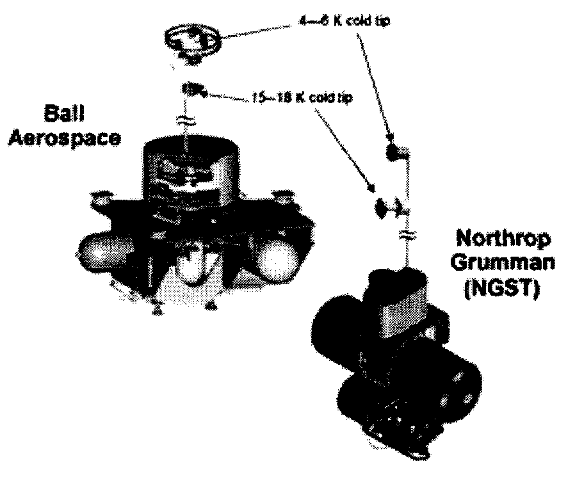

Fig. 5. Ball and NGST ACTDP coolers: The cooler body resides and rejects heat at the main spacecraft bus. The lines to the individual heat sinks can be many meters in length. Each cooler is shown with a single heat sink at 15–18 K and at 4–6 K, but multiple heat sinks could be installed. The Ball cooler has demonstrated 3.6 K on the colder sink, using 3He rather than 4He.

4.2.2 Active cooling for structure and telescope

The cryocoolers currently under development in the Advanced Cryocooler Technology Development Program (ACTDP), managed jointly by JPL and NASA GSFC, are typical of what will be applied to cool the structure and optics for SAFIR. Performance demon-strated to date includes heat lift of 1 W at 40 K, or 0.3 W at 15 K, or 0.1 W at 10 K, available from a single cooler for ~60 W input power. An additional stage provides simultaneous lift of 35 mW at 6 K, or 12 mW at 4 K, for an additional ~60 W input power. One cooler will intercept heat at ~40 K within the multiple radiation shield structure to remove conducted loads from the colder shields; this may be repeated at one higher temperature. Another cooler will intercept heat at the telescope mast, possibly at two different temperatures to optimize power. With the coldest radiation shield at ~15 K, the conducted load to the telescope reflector elements can be reduced to less than 30 mW; the support mast will be cooled to the temperature of the reflecting elements by the second stage of the active coolers, leaving only the thermal power radiatively coupled into the telescope to be extracted from the reflecting elements. Fig. 5 shows two of the ACTDP cooler configurations under development. The Ball cooler has demonstrated cooling to 3.6 K using 3He in the J-T stage. The NGST cooler would be expected to behave in similar manner with 3He; it has demonstrated 5 K with 4He in the J-T stage.

4.2.3 Telescope reflector elements, baffles, and structure

Active cooling will be required to achieve telescope reflective surface temperatures in the range of 4 to 6 K. Emitted power in the 20 to 300 μm band increases by a factor of nearly 100 for a source temperature change from 4 K to 6 K, so the reflector temperature requirement is likely to be determined only by the attainable detector NEP. We assume that the final temperature requirement will be essentially 4 K in the analysis of overall cooling requirements.

Due to its size, the primary reflector will likely be formed of several segments which are deployed into position after launch; heat must be extracted from each of the elements to maintain an even 4 K temperature. The total power absorbed by a 10 meter diameter reflector from the combination of the zodiacal light and the coldest radiation shield is approximately 10 mW. This heat may be deposited unequally over the reflective surface, if the FOV to the coldest radiation shield differs across the telescope; it may also change with repointing for the same reason. The ACTDP low-temperature stage provides a supply of cold helium gas which can flow to heat exchangers located on or within the individual reflector elements; splitting the flow allows balancing the heat lift requirements from elements with different heat lift requirements. Alternatively, separate flow loops of helium gas or gas+liquid mixture, pre-cooled by the ACTDP cold stage, can be circulated to lift heat from separate reflector elements. The use of 2-phase gas+liquid has considerable advantages in providing a uniform heat sink temperature at widely separated locations independent of the heat lift at any point. The temperature at which the liquid evaporates is determined only by the gas pressure, so the temperature remains quite constant within separate heat exchangers. Each heat exchanger evaporates as much liquid as is required to maintain its temperature, so load balancing is automatic and responds immediately to load changes. Such a system has been delivered for use in the Planck spacecraft, in which liquid hydrogen is generated and then circulated to heat exchangers at constant temperature on separate instruments.

Fig. 6 shows the Planck Cooler Cold End ready for integration with the gas piping, which will provide constant temperature heat lift at two instruments.

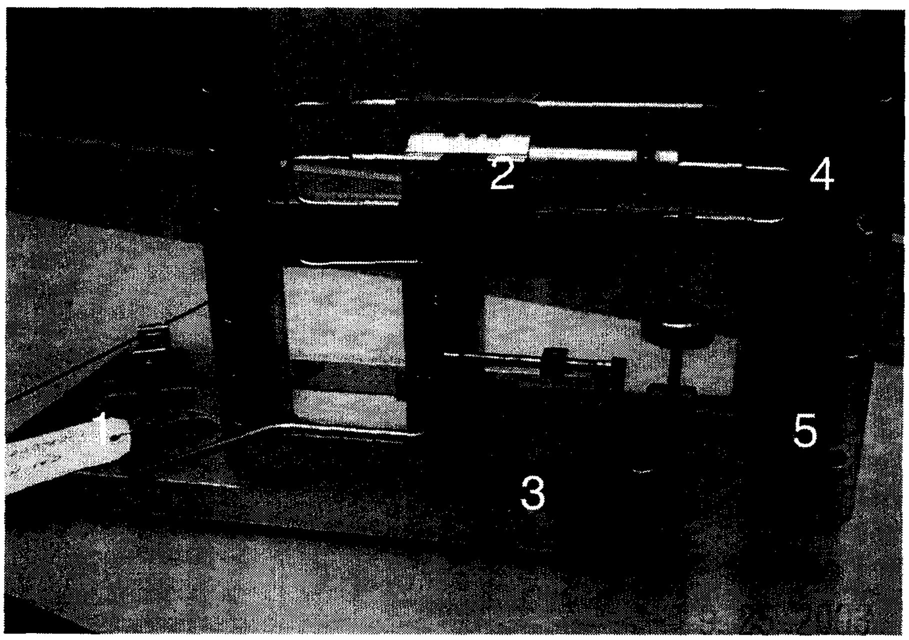

Fig. 6. Planck Cooler Cold End on assembly fixture, ready for integration with Piping Assembly. Two-phase liquid+vapor hydrogen at 19 K cools two instruments. 1. Heat exchanger to HFI; 2. Heat exchanger to LFI; 3. Joule-Thomson expansion valve (looks like ¼" tube); 4. Input/Ouput coaxial flow tubing; 5. Filter

In a telescope with multiple deployed elements, it is likely that individual reflector elements will not be in good thermal contact with each other as a result of the deployment method and the need to maintain freedom of motion for optical alignment. The ability of a fluid-flow cooling system to make thermal contact to several elements with a single constant-temperature flow loop will provide a lightweight, easily deployed system for thermal contact at multiple points and/or to multiple reflector elements.

5 SUMMARY

The Single Aperture Far Infrared (SAFIR) Observatory is a 10-meter class space-based telescope that will study the important and relatively unexplored spectral region between 20 and 1000 μm. The SAFIR Observatory will take advantage of the technology developed for the James Webb Space Telescope, but a thermal architecture design that goes beyond the sunshades developed for the James Webb Space Telescope will be necessary to achieve the desired sensitivity of SAFIR. Similarly, the SAFIR Observatory will take advantage of telescope technologies developed for the James Webb Space Telescope, but differences in the optical design for the telescope, mirror surface material, and how the aperture is put together may be required to fulfill the potential scientific return of SAFIR. Studies are underway at the California Institute of Technology's Jet Propulsion Laboratory to examine two of the principal enabling technologies, the telescope optics and the spacecraft thermal architecture, in order to realize the promise of SAFIR.

REFERENCES

1. C. Dragone, *IEEE Trans. Ant. Prop.* **AP-30**, 331, 1982.
2. B. Claydon, *Marconi Review,* **1st quarter**, p. 14, 1975.
3. D. Lester, D. Benford, A. Blain, et al., SPIE Publ., **Vol. 5487** (in press), 2004.
4. K. Schwarzschild, *Astr. Mittheilungen Kognigl.*, Sternwarte Göttingen, **10**,1, 1905.
5. D.J. Schroeder, *Astronomical Optics*. Academic Press, 1987.