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FAR INFRARED OBSERVATORIES IN SPACE

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Subject headings:

1. SUMMARY

Many of the most exciting and most-studied objects in the sky are brightest at far-infrared (FIR) wavelengths where the Earth's atmosphere blocks the passage of any light. To study these objects therefore requires instruments on satellites. Canadian scientists have worked with virtually all of the major FIR missions and continue this today with participation in the recently (mid–2009) launched Herschel Space Observatory. In this white paper we discuss the next steps in this progression of evermore capable FIR observatories and what future facilities will be needed, especially after Herschel ceases operations in 2012.

Studies in the FIR focus on the processes involved in the formation of structure in the Universe: the formation of galaxies, stars, planets, and the evolution of the interstellar medium. The presence of dust within these objects renders most of the energy produced in these processes into FIR emission. Technical advances in FIR observatories in the past 25 years have yielded greater sensitivity, the ability to cover larger areas in the sky, and most recently achieved higher spectral resolution. Future observatories will continue to improve in these areas, but the one area that has been lacking so far is in achieving significant improvements in *spatial* resolution, comparable to what has been possible in other wavelength ranges.

The Far-InfraRed Discipline Working Group (FIRDWG) was convened by the Canadian Space Agency to examine the possibilities for Canadian involvement for future generations of FIR observatories. The FIRDWG recommended Canadian participation in

- short term: *SPICA*, a Japanese led 3.5 meter MIR/FIR observatory with a cold mirror that will be 100 times more sensitive than Herschel
- medium term: an interferometer such as *SPIRIT*, a US led direct-detection mission that will improve FIR spatial resolution by a factor of 100 over previous missions
- probably on a longer time-scale: *SAFIR*, a US led very large, cold, single-aperture FIR observatory
- balloon experiments: Canadian scientists have been very succcessful in using these much less expensive instruments to access the submm wavelengths and this technique shows great promise for the FIR too.

2. FAR-INFRARED SCIENCE

The integrated power in the FIR background of the Universe is second only to the Cosmic Microwave background – the energy density of ultraviolet/visible light in the Universe is significantly smaller than either the FIR or the CMB. However, while the CMB and the UV/visible have both been well studied – in fact the entire sky has been well mapped in both – this is not true in the FIR with only a very low resolution all-sky map done by IRAS in 1983. The answers to some of the most important science questions that are currently active areas of research require a new generation of FIR facilities. Here we summarize some particular problems that need the facilties. Please see the white papers by Johnstone *et al.* , Barmby *et al.* , Matthew *et al.* , and Scott *et al.* for more and better descriptions of such questions.

2.1. *The formation of planets*

A critical stage in the collapse of a cloud of gas to form a young star involves the formation of a rotating gaseous disk. The bulk properties of the dust grains evolve during this process, causing changes in the FIR/submillimetre spectral energy distribution which can be measured if the disk can be resolved. In the nearest systems, angular resolutions of 0.1–1 arcseconds should be sufficient to resolve disks comparable in size to our own solar system. This is precicesly the size scale that *SPIRIT* will be designed to examine.

The radial density and temperature gradient in these disks sets up a corresponding chemical gradient, one important feature of which is the ice line, the radius at which water vapour condenses to form icy mantles around the rocky grains. Beyond the ice line it is possible to form massive planets more quickly, while inside the ice line only limited quantities of rocky material are available. Emission from ices are found through the mid and far-infrared. *SPICA* will provide the capability to study the broad ice emission bands with its moderate spectral resolution but great sensitivity.

Forming planets can leave kinematical signatures in the disk itself. These features should be easiest to see in the far-infrared, where the emission from the dusty disk is at its peak but will require high spectral resolution to distinguish the kinematical features, such as will be available with *FIRI*, a heterodyne interferometer mission.

2.2. *Cloud cores and embedded stellar content*

Stars form from high density gas cores embedded in a more diffuse gaseous environment. While recent observations have made a lot of progress in mapping out the earliest phases of star formation, the formation of the most massive stars (10–100 times the mass of our Sun) is less well-understood. These relatively rare objects are typically found at larger distances from the Sun and also form preferentially in groups and clusters. Thus, high resolution is critical to separating individual massive stars in formation from their surrounding environment. Far-infrared maps with 1 arcsecond resolution would allow astronomers to distinguish all but the most compact multiple star systems in nearby regions of massive star formation and remove an important ambiguity to our understanding of how massive stars form. *SAFIR* will be the only instrument with both the sensitivity and angular resolution to make these measurements.

2.3. *HD observations for total molecular gas mass*

The HD molecule is potenetially the best tracer for gas mass in most environments where H_2 dominates the mass. HD is found in an abundance of slightly greater than 10^{-5} of the H_2, similar to the usual molecular tracer CO. HD is a strongly emitting molecule in its lowest rotational transition and this emission is not strongly affected by temperature, density (it is optically thin), or chemical effects (very little chemical fractionation occurs, unlike in other deuterated molecules). The other alternative for tracing mass is using dust; however the use of dust for mass (column density) measurement is dependent on the physical characteristics of the dust. In the past it has been assumed that all dust is the same, or at least very similar, but this assumption has been challenged a number of times in the past few years. Also, it is certain that in dense circumstellar disks, where planets are forming, the dust must change substantially as the solid particles grow from sub-micron size to the size of the Earth! In such environments dust is a very uncertain mass tracer.

However the preferred emission line from HD is at a wavelength of 112 microns, in the centre of the FIR band where the Earths atmosphere is most opaque. Subarcsecond resolution and spectral resolution of at least R=3,000 is needed for HD studies of disks. The PACS instrument of Herschel is capable of detecting the HD line but only at resolutions too poor for most objects of interest. ALMA will be unable to observe at the frequency of the HD line. HD studies of disks will be only possible with one of the interferometers such as *SPIRIT* or the balloon-borne Z-Int.

2.4. *Polarization in many environments as a probe of magnetic field morphology*

Magnetic fields provide an important source of support against gravitational collapse in the dense clouds and cores where stars form. Magnetic fields are also thought to be intimately related to the large-scale supersonic turbulence which is seen in these regions. The strength and morphology of magnetic fields is a key prediction of star formation theories; however, relatively little is known about the morphology and strength of magnetic fields in star-forming regions. Polarized far-infrared emission from dust grains would have a unique sensitivity to magnetic fields by working at wavelengths near the peak of the emission spectrum. Observing from space would have the additional advantage that magnetic field morphologies could be mapped over a much broader range of angular scales than comparable observations from the ground at millimetre wavelengths. This is because ground-based observations must chop or rapidly scan the sky in order to remove the time-variable effects of the Earth's atmosphere. Studies of magnetic fields will require sensitive heterodyne instruments such as those that will be available on *SAFIR*, and perhaps of *SPICA*. Dedicated balloon experiments to measure polarization are already under development.

2.5. *Mass loss in evolved stars and the formation of complex molecules*

Low- and intermediate mass stars in late stages of their evolution lose most of their mass through slow (~ 10 km/s) but massive (up to $\sim 10^{-4} M_\odot$/yr) dust-driven outflows, and thus are the main injectors of gas and dust into the interstellar medium. These objects have been well studied at mid-infrared wavelengths, but such observations are only sensitive to the warm material close to the central objects, and thus represent only a snapshot of the most recent mass loss. Mass loss rates show large variations over time, and thus such studies are not representative of the mass loss process as a whole. Herschel will offer a first glimpse of the far-IR dust emission of evolved stars. Herschel's large beam size and sensitivity will only allow a handful of nearby objects to be studied though.

Dust only represent a small fraction of the mass, and especially in carbon-rich AGB stars, photochemistry results in the formation of a whole set of complex molecules. To date, more than 60 molecular species have been detected in the outflow of the prototypical carbon star IRC 10+216. It is believed that carbon stars are the sites of the formation of Polycyclic Aromatic Hydrocarbons (PAHs). The far-IR range is uniquely sutied to identify individual PAH species. In addition, molecular lines at those wavelengths are used as tracers for the physical parameters and dynamics in these outflows. A sensitive far-IR mission at high spatial resolution, such as *SPIRIT* or SAFIR can thus at the same time study the chemistry and the physics of the mass loss process at large.

2.6. *Local galaxies*

Nearby galaxies allow us both to place our own Galaxy in the broader context of galaxy properties and evolution and also to study environments that are substantially different from those found in our own galaxy, including regions with extremely high star formation rates or low abundances of heavy elements. Observations at far-infrared/submillimetre wavelengths for all but the nearest galaxies are hampered by the limited resolution and sensitivity of previous instruments. While Herschel will be a large step forward in this regard, its angular resolution corresponds to scales of many kiloparsecs in the vast majority of nearby galaxies. Instruments with higher angular resolution (approaching 1 arcsecond) would allow astronomers to study the gas and dust and the stars that form from them on spatial scales of less than a kiloparsec in galaxies out to distances of 200 Mpc. This volume of space contains numerous examples of unusual galaxies, such as galaxies undergoing intense bursts of star formation and galaxies containing active nuclei powered by a central massive black hole. With the capability to study many galaxies of a given class, rather than just the single nearest object, we will place our understanding of galactic evolution on a much firmer footing. *SAFIR* will be the instrument of choice for such studies.

2.7. *Galaxy Formation and Evolution: Resolving the Cosmic Infrared Background and the History of Cosmic Star Formation*

In spite of the many recent observational advances in this area, there remains a glaring disconnect between standard cosmological theories of large scale structure formation and our understanding of structure growth on galaxy scales. Indeed the relatively simple physics of the now standard precision cosmological model (Λ–CDM) cannot predict the complex physics of regions of the universe dominated by baryonic matter. It is clear that the local environment of galaxies plays an important role in their evolution in ways we do not understand, and that there is a tight connection of uncertain nature between the growth of the supermassive black holes in the centers of all massive galaxies and their stellar components.

A powerful mid-far-infrared mission will fill an important niche in extragalactic astronomy. The mid and far-infrared region will probe hotter components of galaxies than ALMA (which samples cold processes), such as thermally emitting hot dust surrounding AGN and star-forming (HII) regions. Many important ionic transition lines and PAH features, key for studying the physics of star formation and AGN activity are found shortward of ALMA's shortest wavelength. Given that the outstanding questions of galaxy formation focus on the progression and nature of star formation, the feedback between AGN and star formation, and the physics which drives this activity, sensitive probes of these processes are crucial. Both *SPICA* and *SAFIR* will be crucial tools for such studies.

3. FUTURE FAR-INFRARED INSTRUMENTS

The FIRDWG was assembled to review the instruments that might be available for Canadian participation after Herschel. The main questions were: (1) should the next FIR mission be a single antenna mission, like Herschel, or an interferometer; and (2) should the first FIR interferometer mission be a direct detection or heterodyne instrument? The answers depend on both the science questions to be addressed as demonstrated in Section 2 above, and on the technology available which we summarize here. The most interesting projects are listed in the attached table and some additional notes on each appears below.

For single antenna missions, the size and the temperature of the dish are key: e.g., SPICA will improve upon Herschel by using a much colder antenna. This will improve the sensitivity for all instruments but will offer the biggest improvement (a factor of at least 100) to direct detector instruments. Thus, projects requiring photometry or low-to-medium spectral resolution benefit. To gain in spatial resolution and to make greater gains in sensitivity requires a significantly larger antenna. In order to fit within a launch vehicle, such antennae will require deployment in space (e.g. unfolding antenna mirror panels as for the JWST), which is both technically challenging and a great deal more expensive.

Interferometers offer a large improvement in spatial resolution over a single antenna. Direct detection interferometers will consist of 2 or 3 antennae that reflect the incident light into a beam combiner. Heterodyne interferometers can consist of a large number of antennae but must share a common Local Oscillator (LO) signal. Both methods have the challenging requirement to measure and control distances between optical elements (the antennae) and both methods can be used with either free-flying (separate satellites) or connected (via boom or tether) antennae. The direct detection interferometer teams are currently leaning towards antennae on a single structural element while the heterodyne teams favour free-flying antennae. The major challenges for direct detector missions is that current detectors (e.g. TES detectors as in SCUBA-2) are two to three orders of magnitude too noisy for these missions. There are a number of promising technologies suggested by recent research teams but all are far from being well understood. Heterodyne detectors are only slightly better off: the low noise SIS receivers available now cannot be used at frequencies above approximately 1.5 THz and the Hot Electron Bolometers used at higher frequencies are much noisier. In addition, producing a tunable LO signal at THz frequencies is difficult. See the white paper by S. Claude for more details on these problems – and possible solutions.

3.1. *Notes on specific missions*

Z Int: A two element interferometer can be constructed to be carried on a balloon, with one antenna hanging below the other – in the 'z' direction, and therefore called a "Z Interferometer". This is only one of a number of of potentially very interesting balloon experiments receommended by the FIRDWG who felt that this technique provides an exciting possibility for pathfinder missions led by Canadians.

SPICA: The Japanese led SPICA mission (Figure 1) is proposed to carry 3 instruments: a Mid-IR Coronograph, a Mid-IR Imaging Spectrometer, and a Far-IR Imaging Spectrometer. ESA has recently committed funding for this mission and the CSA is funding the Canadian participation which will take advantage of Canadian expertise in imaging FTS technology. A final positive decision from the Japanese space agency JAXA is expected shortly.

FIRI: The Far-InfraRed Interferometer (FIRI) is a mission proposed by a large pan-European team. This proposal calls for a very flexible observatory with a combination of both heterodyne and direct detection instruments on a few large anntennae.

SPIRIT: The Space Infrared Interferometric Telescope (SPIRIT, see Figure 2) is a mission under development at NASA. It consists of two telescopes cooled to 4 K and mounted on trolleys on a deployable structure. The telescopes move along the structure providing baselines from 6 m to 36 m while the entire structure rotates. The spatial resolution of SPIRIT is compared to other instrument in Figure 3.

SAFIR: The Single Aperture Far InfraRed Observatory (SAFIR) is a long-term project under development by NASA. One proposed version of SAFIR is shown in Figure 4.

3.2. *FIRDWG recommendations*

The missions recommended by the FIRDWG are as listed at the beginning of this white paper in the Summary section. To achieve a reasonable degree of participation in these missions the FIRDWG also recommended continued development support by CSA to groups across Canada.

TABLE 1
FIR PROPOSED MISSIONS

Name	Type	Size	Resolution (arcsec)	Launch Date	Remarks
Z Int	interferometer	2 x 3m at 100m	0.3	2014	balloon borne
SPICA	single dish	3.5m	0.35	2018	<5K telescope
SPIRIT	interferometer	2 x 1m at 36m	0.08	2023	direct-detection on boom
FIRI	interferometer	3 x 3.5m at 1km	0.02	2023	heterodyne free-flying
SAFIR	single dish	10m	1.0	2028	cold telescope

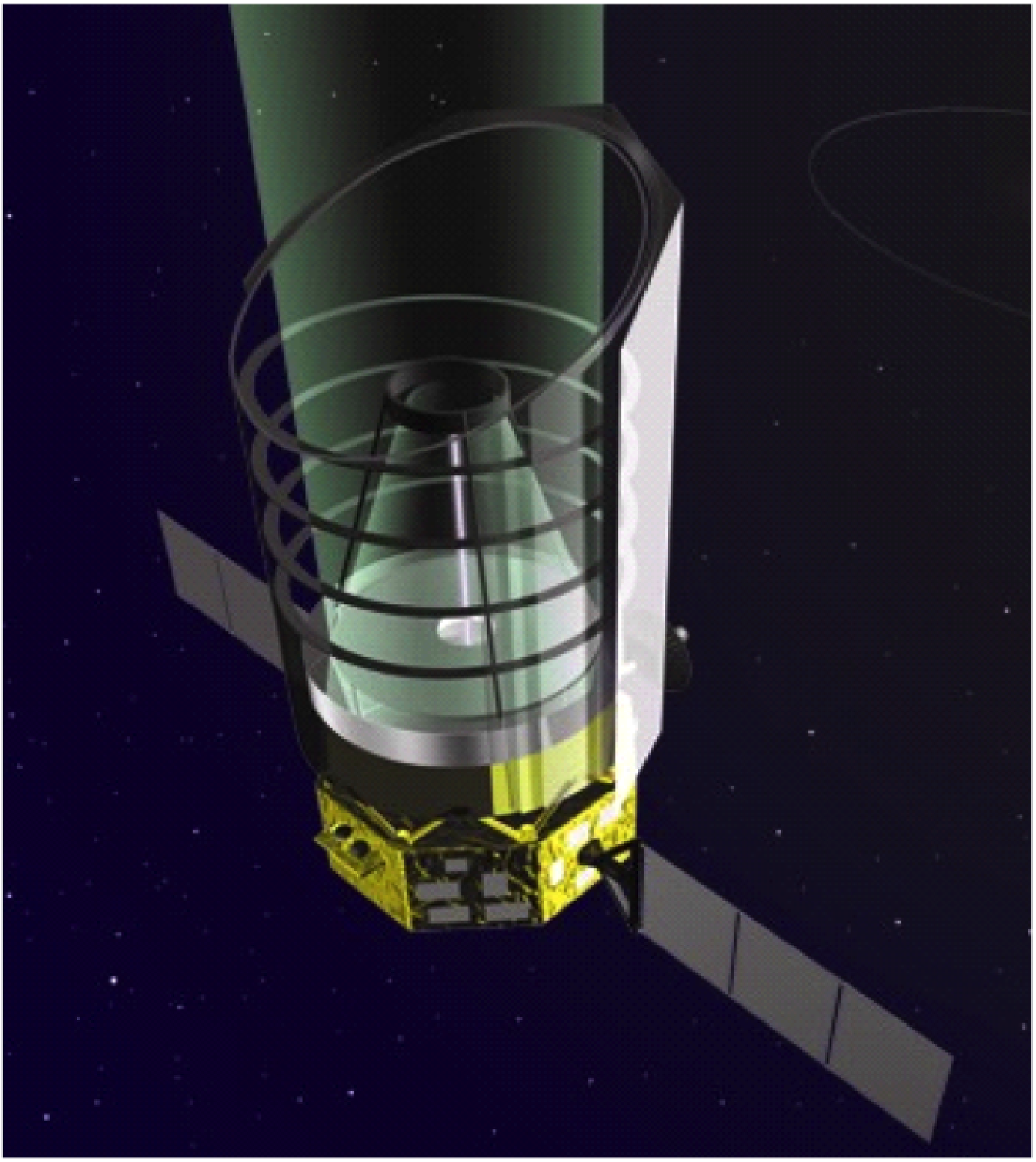

Fig. 1.— The SPICA satellite

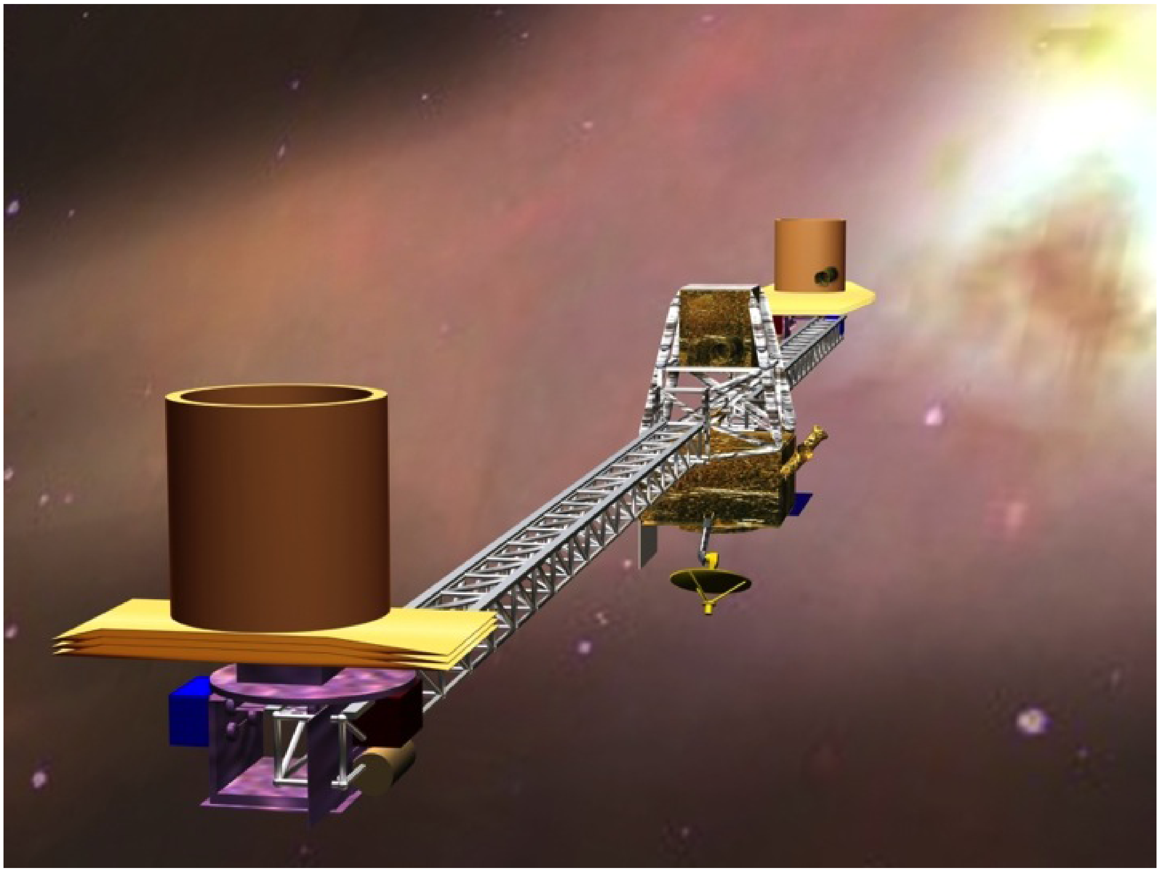

FIG. 2.— Concept drawing of the NASA SPIRIT satellite

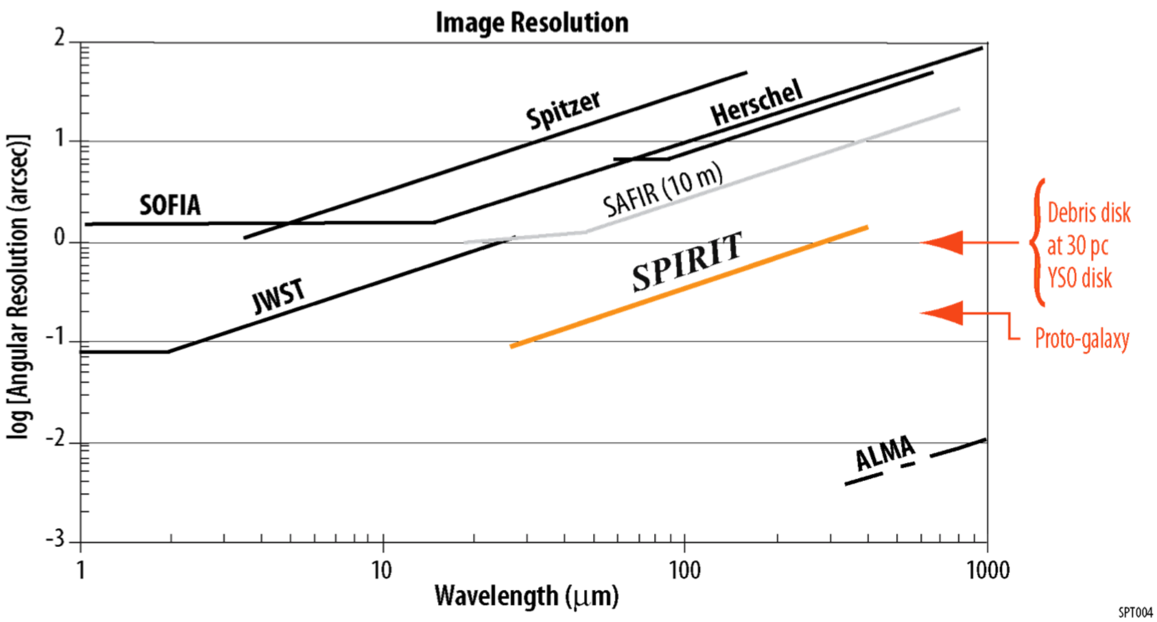

Fig. 3.— Spatial Resolution of the NASA SPIRIT satellite compared to other instruments.

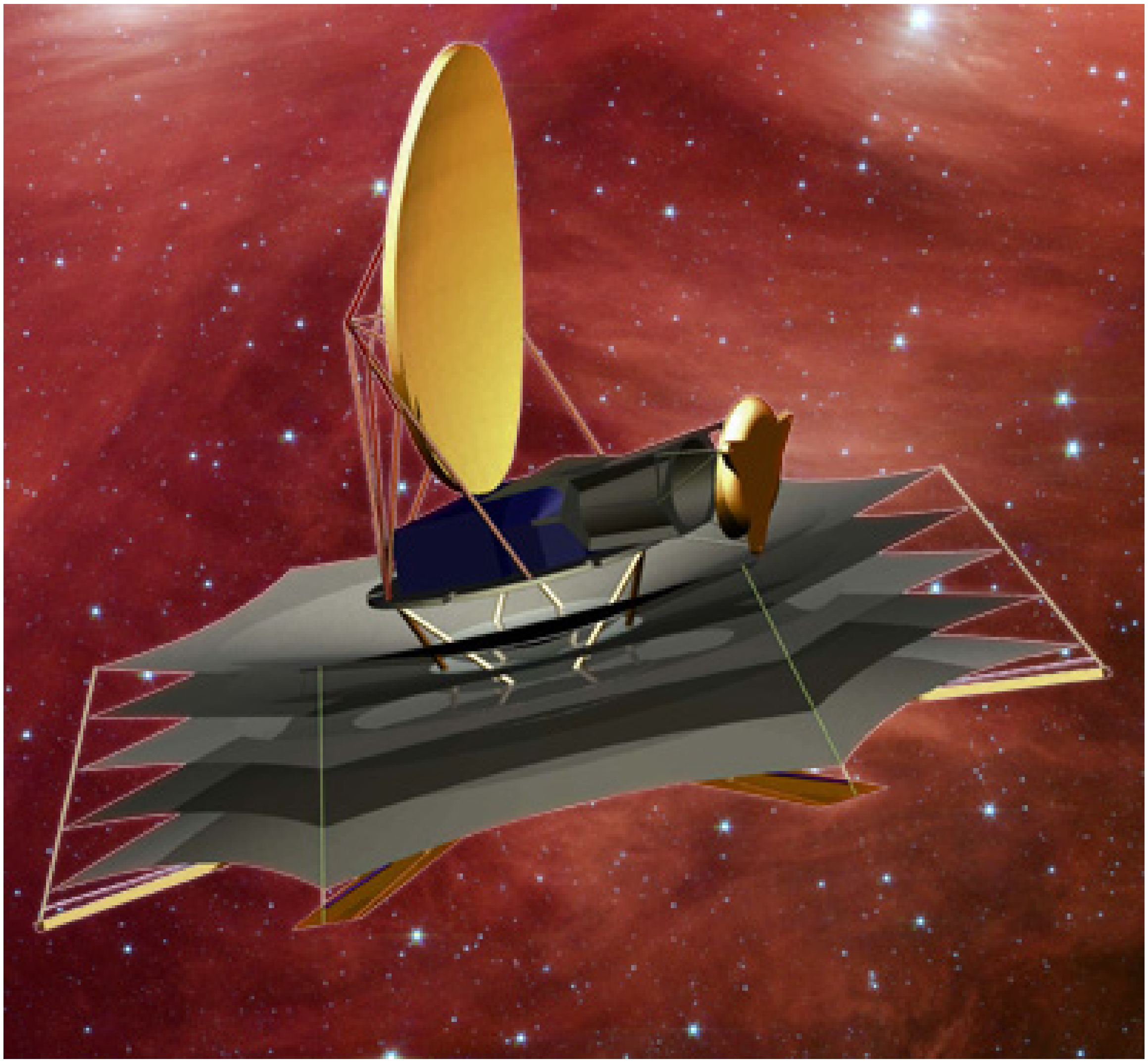

Fig. 4.— The “CALISTO” version of a SAFIR mission