A Mission Whitepaper submitted to the 2010 Decadal Survey Activity RFI

Stellar Imager (SI) – A UV/Optical Interferometer (UVOI) Viewing the Universe in High Definition

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I. Key Science Goals

Stellar Imager (SI) is a space-based, UV/Optical Interferometer (UVOI) with over 200x the resolution of HST. It will enable 0.1 milli-arcsec (@2000 Å) spectral imaging of stellar surfaces and the Universe in general and open an enormous new "discovery space" for Astrophysics with its combination of high angular resolution, dynamic imaging, and spectral energy resolution. SI's goal is to study the role of magnetism in the Universe and revolutionize our understanding of:

- **Solar/stellar dynamos and magnetic activity and their roles in the formation and evolution of stars and in the habitability of planets**
- **Mass transport processes and their roles in the formation, structure, and evolution of stars and stellar systems**
- **Active Galactic Nuclei (AGN) and their role in galaxy formation and evolution**

At this resolution, sequences of images will also reveal the dynamics of astrophysical processes and allow us to directly see, for the first time, the evolution of, e.g., active-region-scale magnetic fields of Sun-like stars, a planetary nebula, an early supernova phase, mass exchange in binaries, (proto-)stellar jets, and of accretion systems. The UV capability of SI allows imaging of high temperature plasmas that cannot be obtained from the ground. This *Cross-Theme* mission addresses major Science Questions and Research Objectives in the 2007 NASA Science Mission Directorate Science Plan (Plan Table 2.1) in both Astrophysics and Heliophysics.

The SI mission is targeted for the mid 2020's – thus significant technology development in the upcoming decade is critical to enabling it and future space-based sparse aperture telescope and distributed spacecraft missions. The key technology needs include: 1) precision formation flying of many spacecraft, including precision metrology over km-scales, 2) closed-loop control of many-element, sparse optical arrays, and 3) methodologies for ground-based validation of such systems. **It is critical that technology development for this mission occur during the 2010 decade to enable a launch of this Great Observatory class mission in the last half of the 2020 decade.**

SI is an implementation of the UV Optical Interferometer (UVOI) in the 2006 Astrophysics Strategic Plan and a Flagship "Landmark/Discovery Mission" in the 2005 Heliophysics Roadmap. It is a NASA Vision Mission ("NASA Space Science Vision Missions" (2008), ed. M. Allen) and has also been recommended for further study in an NRC Report (2008) on missions potentially enhanced by an Ares V launch, although the baseline mission design can be launched using existing EELV's (e.g., a Delta IV H).

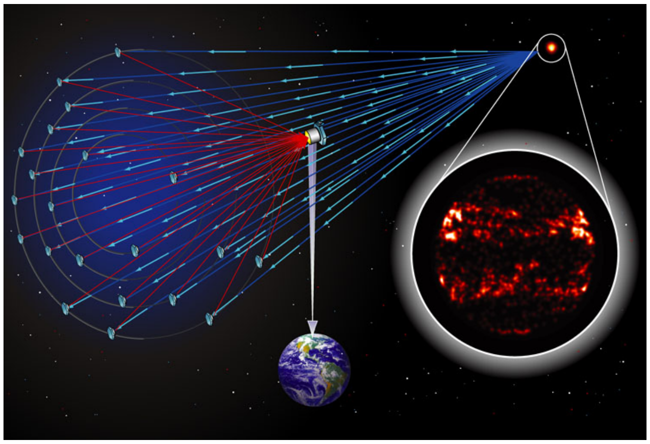
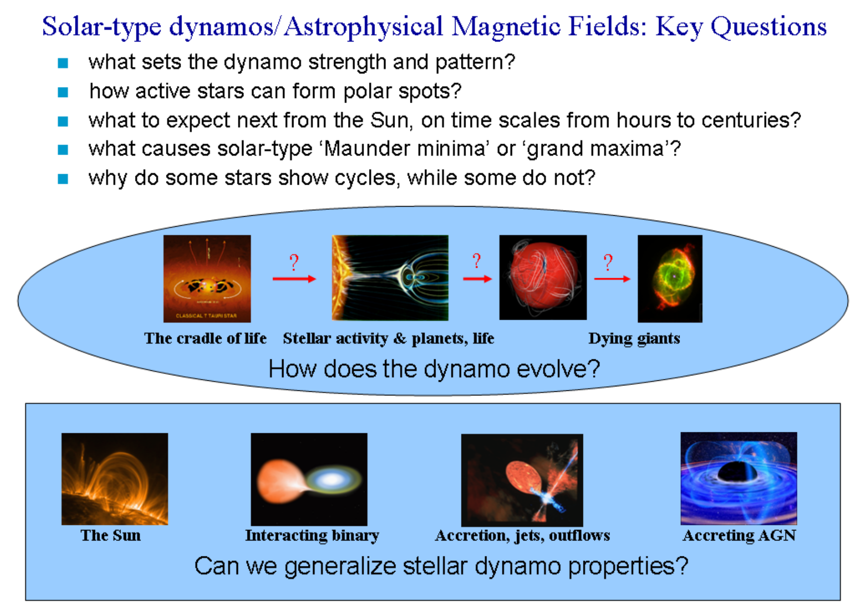


Figure 1: An array of 20-30 one-meter mirrors fly in precision formation to form a virtual parabola 100-1000m in diameter to enable sub-milliarcsec spectral imaging of a wide variety of astronomical objects, such as the solar-type star shown above in the light of CIV emission lines.

The full SI Vision Mission (VM) Study report, related science and technology whitepapers, and additional information can be found at: http://hires.gsfc.nasa.gov/si/. We first discuss 3 primary science goals of SI in further detail (see the VM Report for other science goals), and then outline the mission architecture, technology needs, and estimated cost.

A. Understanding Dynamos and Magnetic Activity in the Sun & Stars and their role in the formation, structure, and evolution of stars and in the habitability of planets

A magnetic dynamo operates in all stars at least during some phases in their evolution. It regulates the formation of stars and their planetary systems, the habitability of planets, and the space weather around them. Dynamos also operate in objects including planets, accretion disks, and AGN (Fig. 2). Although we know that flows in rotating systems are essential to such dynamos, there is no comprehensive dynamo theory from which we can derive the strength, the patterns, or the temporal behavior of stellar magnetic fields. Understanding the complex of non-linear couplings in a dynamo requires that we combine numerical studies and theory with observations of the evolving surface field of Sun and stars, of the average properties of magnetic fields in a large sample of stars, and of stellar internal flows. *These observations will enable us to constrain the source and sink properties of the surface magnetic field, by measuring the latitudinal and longitudinal flux-emergence patterns, the flux dispersal rate, and the differential and meridional flows. These properties are both important input parameters to flux-transport models and sensitive differentiators between dynamo models.* (see Schrijver et al. 2009 Decadal Science Whitepaper for further information and references).



Solar-type dynamos/Astrophysical Magnetic Fields: Key Questions

- what sets the dynamo strength and pattern?
- how active stars can form polar spots?
- what to expect next from the Sun, on time scales from hours to centuries?
- what causes solar-type ‘Maunder minima’ or ‘grand maxima’?
- why do some stars show cycles, while some do not?

How does the dynamo evolve?

Can we generalize stellar dynamo properties?

Figure 2: SI addresses major questions on dynamos and magnetic fields.

For cool stars like the Sun, dynamo action persists from the very formation of the star throughout its existence as a fusion reactor. The Sun’s activity is modulated significantly from cycle to cycle, sometimes persistently for several decades. Activity decreased, for example, for decades in the 17th Century when Earth experienced the Little Ice Age. Observations of other cool stars are crucial to our understanding of solar/stellar dynamo action. This has taught us, for example, that convection is part of all solar-like dynamos, and that rotation regulates their strength. But we do not have a theory that explains why stars are as active as they are, why some show cycles and some do not, what causes the Sun’s cycles to differ from one to the next (e.g., the extra long duration of the current Cycle 23), and how a cyclic dynamo can restart after a Maunder-like (e.g. Little Ice Age) minimum. Hence, we cannot usefully forecast long-term space weather or reliably model the effects of stellar magnetism on the evolution of stars, planetary systems, planetary atmospheres, and thus the habitability of a planetary system.

Numerical modeling has taught us valuable lessons about dynamos, including the fact that they are highly non-linear processes that couple scales across the full convection zones of stars down to the smallest convective scales. Our computer models are therefore of necessity simplified, and hence require observational guidance from stars with a variety of properties. *Key to successfully developing a predictive dynamo theory is the realization that we need a population study: we need to study the evolution of dynamo-driven activity in both latitude and longitude in a sample of stars like the Sun, and compare it to observations of young stars, old stars, binary stars, etc.* The potential for a breakthrough in our understanding lies in spatially-resolved imaging of the dynamo-driven emission patterns on this wide-ranging stellar sample. These patterns, and how they depend on stellar properties (such as convection, (differential) rotation and helicity, meridional circulation, evolutionary stage/age, …), are crucial for dynamo theorists to explore the sensitive dependences on many poorly known parameters, to investigate bifurcations in a non-linear 3D dynamo, and to ultimately validate a model. Observations of light-curves give us some information, but more is needed. (Zeeman) Doppler imaging can be used to obtain information on surface manifestations of magnetic activity for moderate and rapid rotators, but the slowest rotators (the majority of desired targets) require long baseline, interferometric imaging. Ground interferometers will provide information on stellar diameters, limb darkening, and other atmospheric parameters, especially on evolved stars, but cannot image magnetic activity patterns on solar-type stars in detail. *Direct UV/optical interferometric imaging* (0.1 mas observations in UV emission lines of magnetically active regions on stellar surfaces) *is the only way to obtain the required information on the dynamo patterns for stars of Sun-like activity.*

To address these science goals, the Stellar Imager is designed to provide UV/Optical sub-mas images and disk-resolved asteroseismology for a significant sample of stars similar to the Sun, as well for other cool stars with very different characteristics. SI will have access to an exciting array of distinct stars and stellar systems (see Fig. 3). An array diameter of 500 m is needed to resolve a medium-sized solar-type active region when observing a Sun-like star at ~4 pc. A km-sized array provides the necessary resolution out to ~8pc. SI will, for the first time, enable imaging of magnetic activity of a variety of Sun-like stars (there are ~3 dozen F, G, K main-sequence (MS) stars within 8pc), many cooler M-type MS stars, including stars with shallow convective envelopes, fully-convective stars, cool, close binary systems with dual active components magnetically coupled at a few stellar radii, compact RS-CVn-type binaries, mass-transferring Algol-type systems, symbiotic systems, and red giant & supergiant stars. Imaging magnetically active stars and their surroundings will also provide us with an indirect view of the Sun through time, from its formation in a molecular cloud, through its phase of decaying activity, during and beyond the red-giant phase during which the Sun will swell to about the size of the Earth's orbit, and then toward the final stages of its evolution (see Figure 4 (left)).

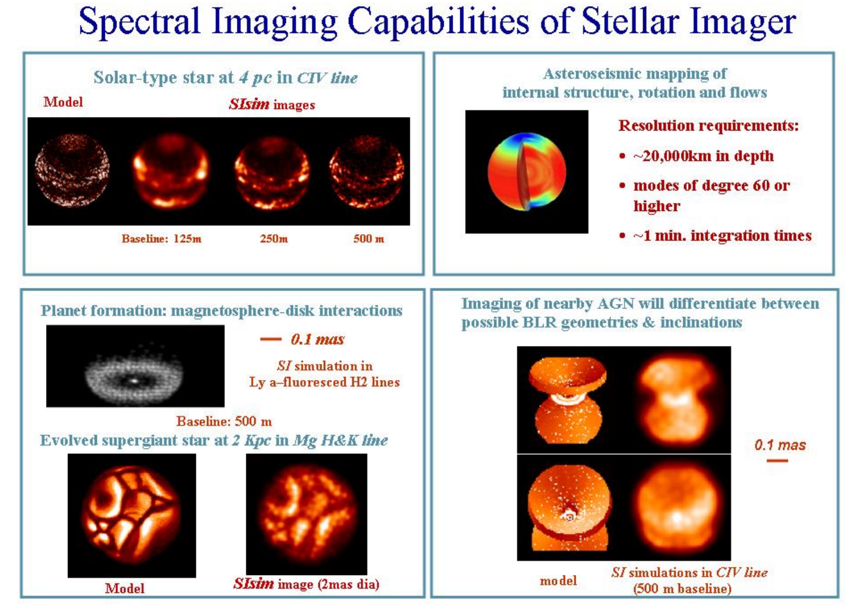


Figure 3: SI"s capabilities will provide UV images of a wide variety of objects at resolutions only previously dreamed of, as seen in these simulations (using 30 mirrors in a non-redundant pattern with indicated max. baselines).

B. Understand Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems

Understanding the formation, structure, and evolution of stars and stellar systems remains one of the most basic pursuits of astronomical science, and is a prerequisite to obtaining an understanding of the Universe as a whole. The evolution of structure and transport of matter within, from, and between stars are controlled by dynamic processes, such as variable magnetic fields, accretion, convection, shocks, pulsations, and winds. Compelling new scientific opportunities for understanding the formation, structure, and evolution of stars and stellar systems are enabled by dramatic increases in UV-Optical angular resolution to the sub-mas level. SI will provide direct spectral imaging of spatial structures and dynamical processes in the various stages of stellar evolution (e.g., Fig. 4, left & center) for a broad range of stellar types. SI provides for dramatically improved observation and understanding of: young stellar systems; hot star rotation, disks, & winds; stellar pulsation across the HR-diagram and its impact on stellar structure and mass loss; convection in cool, evolved giant and supergiant stars; interacting binaries; novae and supernovae (Carpenter et al. 2009 Decadal Science WP, SI VM Report) .

Hours to weeks between successive images (see Fig. 4, right) will provide yet unimaginable real movies of time-series phenomena, e.g., mass transfer in binaries, pulsation-driven surface brightness variation and convective cell structure in giants and supergiants, jet formation and propagation and the changes in debris disks/shells in young planetary systems due to orbiting resonances and planets, non-radial pulsations in and winds from stars, and the structure, evolution, and interaction with the interstellar medium of the core regions of nearby supernovae.

Almost all high-energy sources in the Universe are powered by potential energy released via accretion. Understanding accretion driven flows in binaries, for example, will directly affect our understanding of similar flows around young stellar objects, including the formation of planets in the circumstellar disk, as well as the much larger scale accretion flows in Active Galactic Nuclei (AGNs). Compact, mass transferring binaries (e.g., Algols, cataclysmic variables, symbiotics; see Fig. 4 (center)) will provide us with laboratories for testing energetic processes such as magnetically driven accretion and accretion geometries, and various evolutionary scenarios.

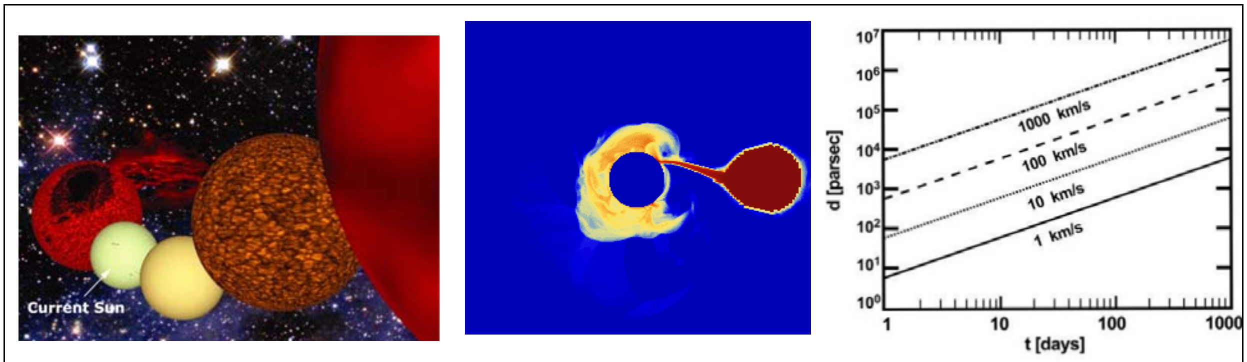


Fig. 4: Examples of SI's capabilities
(left): Evolution of the Sun in time - SI will provide us a view by resolving stars representing each solar era.
(center): Hydrodynamic simulations (Richards, M. T. and Ratliff, M. A. 1998, *ApJ* **493**, 326) of the mass transfer in the Algol prototype β Per (2 mas separation), showing H-alpha emissivity, which can be directly imaged by SI.
(right): Minimum time interval between successive images required to resolve the motion of a feature moving at different speeds, as a function of the object's distance, shows the power of SI's resolution to dynamically image.

C. Understand AGN and their role in Galaxy Formation and Evolution

A fraction of galaxies harbor powerful non-stellar energy sources, AGN, at their gravitational centers. AGN emit radiation at all energies and span a huge range in luminosity, from Low Luminosity AGN and LINERs, to Seyfert galaxies, and, finally, QSOs. AGN are thought to be powered by the accretion of matter by a supermassive black hole (SMBH) in the center of the host galaxy. Relativistic particles are accelerated and collimated along magnetic fields in the inner parts of the disk and ejected along the rotation axis of the SMBH/disk system, sometimes forming extended jets. The UV/optical spectra of AGN are characterized by broad emission lines. Doppler-broadened permitted lines, with full width at half maximum (FWHM) > several 1000 km s^{-1} are thought to form in dense gas in the "Broad Line Region (BLR)" within tens of light days from the central SMBH, while forbidden lines, with FWHM< 1000 km s^{-1}, form in lower density gas in the "Narrow-Line Region (NLR)", which may extend from 1 pc to several kpcs. AGN are divided into Type 1s, which show broad permitted lines and non-stellar optical continua and Type 2s, which have permitted and forbidden lines of similar widths and continua dominated by the host galaxy. The unified model posits that the two types are intrinsically the same but that our line-of-sight to the BLR and accretion disk in Type 2s is blocked by a dusty circumnuclear torus. (see the Kraemer et al., 2009 Decadal Science WP for references/details).

*There are several key questions as to the nature and origin of AGN that can be addressed only by probing their central regions with sub-mas angular resolution at UV/optical wavelengths, including: 1) what initiates the active phase, 2) the duration of the active phase, and 3) the effect of the AGN on the host galaxy***.** Remarkably, the SMBH mass in AGN is roughly proportional to the galaxy bulge mass over more than 4 orders of magnitude, which suggests that the growth of the SMBH has kept pace with the process of hierarchical galaxy assembly. The trigger for the build-up of the SMBH is thought to be major galaxy mergers, which feed the central accretion disk and initiate a burst of star formation. The current paradigm posits that the accumulation of matter in the bulge is halted by the effect of the AGN, i.e. "AGN feedback"'. SI will constrain the dynamics of that AGN feedback by using spectral imaging to map outflows in intermediate redshift QSOs and thus provide new insights for testing models of hierarchical build-up of galactic bulges.

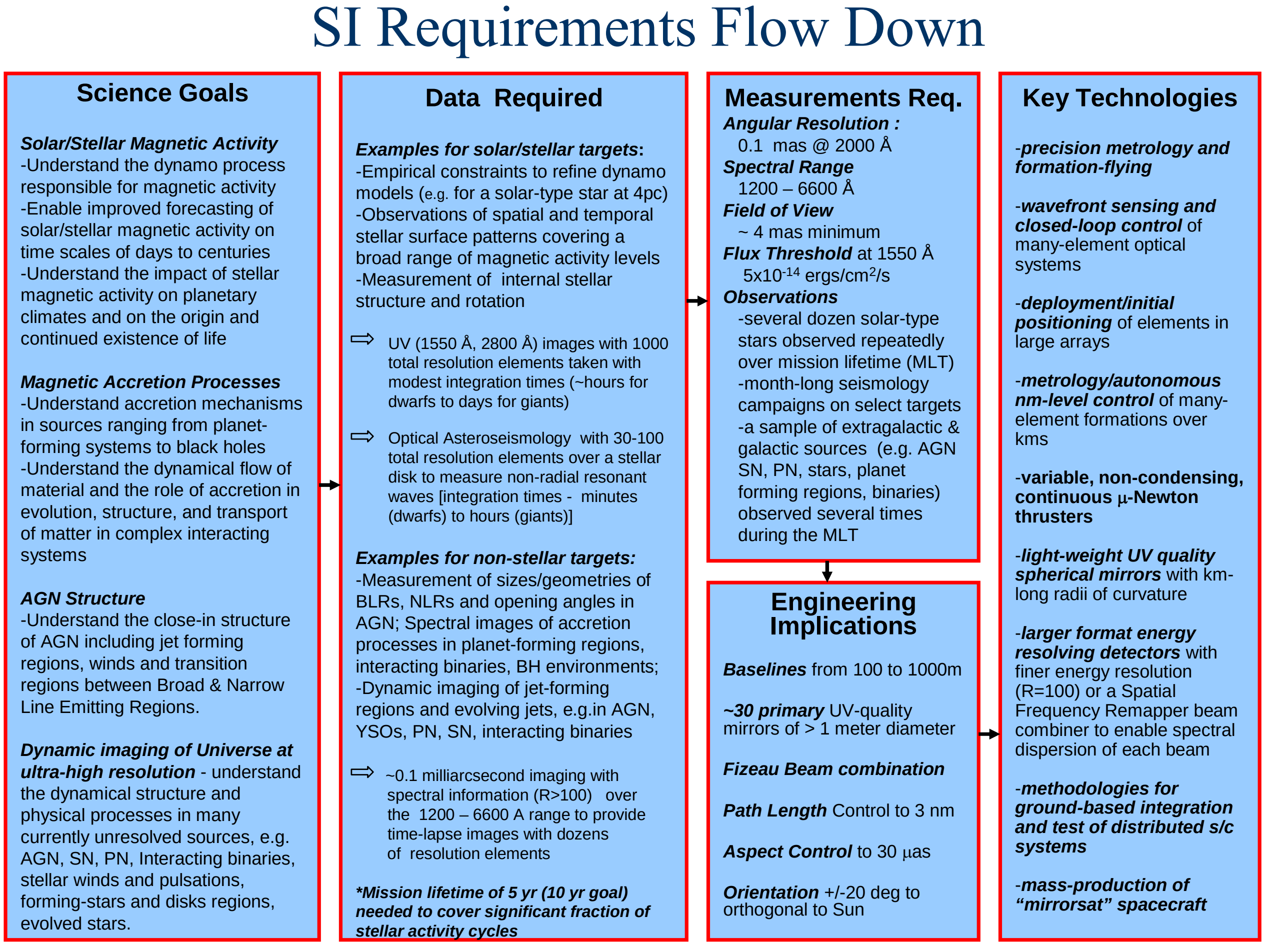
SI will also probe the BLR/NLR transition regions in AGN and give us new insight into how gas is ejected and to trace the launch point of the mass outflow. SI's sub-mas resolution will probe both the torus structure and the BLR/NLR transition region. The minimum radial distance of the inner wall of the obscuring torus is determined from the point at which dust grains will evaporate due to the strong UV flux from the central AGN (i.e., the "sublimation radius"). The survivability of dust grains is also thought to determine the BLR/NLR transition zone. For UV luminosities ~10^{44} ergs s^{-1}, the sublimation radius is ~0.1 pc, which will be easily resolved for nearby Seyfert galaxies such as NGC 1068 or NGC 4151. For QSOs, which are 100-1000 times more luminous, the sublimation radius is on the scale of parsecs. Hence, we will be able to resolve the inner structure of a number of AGN, spread over a range of luminosity/redshift. SI will also be able to resolve the region where the relativistic jet is collimated for its journey of over 7 orders of magnitude in distance into the intergalactic medium. Figure 3 (lower right) shows simulation of an SI CIV observation of the inner ~100 light days of a nearby AGN - SI will resolve the structure of the circumnuclear gas and determine the origin and physical characteristics of mass outflow.

II. Technical Overview

NASA commissioned a “Vision Mission (VM) Study” of SI in 2004-2005, which developed a design that meets the performance requirements required to achieve the science goals described above. The baseline full-mission concept for SI was developed in collaboration with the GSFC Mission Design Lab (MDL) and Instrument Design Lab (IDL). The MDL worked on the overall design of a space-based Fizeau interferometer, located in a Lissajous orbit around the sun-earth L2 point. A variety of disciplines considered the implications of this general design, including power, guidance & navigation, flight dynamics, operations, communications, quality assurance, system engineering, etc. The IDL concentrated its efforts on the design of the beam-combining hub in the context of the selected overall architecture, again from a multiple-discipline viewpoint, and including accommodation of the MDL results. In addition to assisting in the development of the architecture, the Design Labs explored the technical feasibility of the mission and identified the technology developments needed to enable the mission ~2024.

A. Mission Requirements

The SI Team in collaboration with the MDL and IDL defined a detailed flow down of requirements (Fig. 5) from science goals to data and measurements requirements to engineering implications to the key technologies needed to implement the mission.



SI Requirements Flow Down

Science Goals

Solar/Stellar Magnetic Activity
-Understand the dynamo process responsible for magnetic activity
-Enable improved forecasting of solar/stellar magnetic activity on time scales of days to centuries
-Understand the impact of stellar magnetic activity on planetary climates and on the origin and continued existence of life

Magnetic Accretion Processes
-Understand accretion mechanisms in sources ranging from planet-forming systems to black holes
-Understand the dynamical flow of material and the role of accretion in evolution, structure, and transport of matter in complex interacting systems

AGN Structure
-Understand the close-in structure of AGN including jet forming regions, winds and transition regions between Broad & Narrow Line Emitting Regions.

Dynamic imaging of Universe at ultra-high resolution - understand the dynamical structure and physical processes in many currently unresolved sources, e.g. AGN, SN, PN, Interacting binaries, stellar winds and pulsations, forming-stars and disks regions, evolved stars.

Data Required

***Examples for solar/stellar targets*:**
-Empirical constraints to refine dynamo models (e.g. for a solar-type star at 4pc)
-Observations of spatial and temporal stellar surface patterns covering a broad range of magnetic activity levels
-Measurement of internal stellar structure and rotation

⇨ UV (1550 Å, 2800 Å) images with 1000 total resolution elements taken with modest integration times (~hours for dwarfs to days for giants)

⇨ Optical Asteroseismology with 30-100 total resolution elements over a stellar disk to measure non-radial resonant waves [integration times - minutes (dwarfs) to hours (giants)]

Examples for non-stellar targets:
-Measurement of sizes/geometries of BLRs, NLRs and opening angles in AGN; Spectral images of accretion processes in planet-forming regions, interacting binaries, BH environments;
-Dynamic imaging of jet-forming regions and evolving jets, e.g.in AGN, YSOs, PN, SN, interacting binaries

⇨ ~0.1 milliarcsecond imaging with spectral information (R>100) over the 1200 – 6600 A range to provide time-lapse images with dozens of resolution elements

****Mission lifetime of 5 yr (10 yr goal) needed to cover significant fraction of stellar activity cycles***

Measurements Req.

Angular Resolution :
0.1 mas @ 2000 Å
Spectral Range
1200 – 6600 Å
Field of View
~ 4 mas minimum
Flux Threshold at 1550 Å
5×10^{-14} ergs/cm^2/s
Observations
-several dozen solar-type stars observed repeatedly over mission lifetime (MLT)
-month-long seismology campaigns on select targets
-a sample of extragalactic & galactic sources (e.g. AGN SN, PN, stars, planet forming regions, binaries) observed several times during the MLT

Engineering Implications

Baselines from 100 to 1000m

~30 primary UV-quality mirrors of > 1 meter diameter

Fizeau Beam combination

Path Length Control to 3 nm

Aspect Control to 30 μas

Orientation +/-20 deg to orthogonal to Sun

Key Technologies

-***precision metrology and formation-flying***

-***wavefront sensing and closed-loop control*** of many-element optical systems

-***deployment/initial positioning*** of elements in large arrays

-***metrology/autonomous nm-level control*** of many-element formations over kms

-**variable, non-condensing, continuous μ-Newton thrusters**

-***light-weight UV quality spherical mirrors*** with km-long radii of curvature

-***larger format energy resolving detectors*** with finer energy resolution (R=100) or a Spatial Frequency Remapper beam combiner to enable spectral dispersion of each beam

-***methodologies for ground-based integration and test of distributed s/c systems***

-***mass-production of “mirrorsat” spacecraft***

Figure 5: The VM Study produced a detailed requirements flow down from Science Goals to Key Technologies.

B. Space Systems Architecture

The requirements shown in the preceding Section were used in the VM Study to derive the baseline mission architecture shown in Figure 6. The selected design is a space-based, UV-Optical Fizeau Interferometer with 30 one-meter primary mirrors, mounted on formation-flying “mirrorsats” distributed over a parabolic virtual surface whose diameter can be varied from 100m up to as much as 1000m, depending on the angular size of the target to be observed.

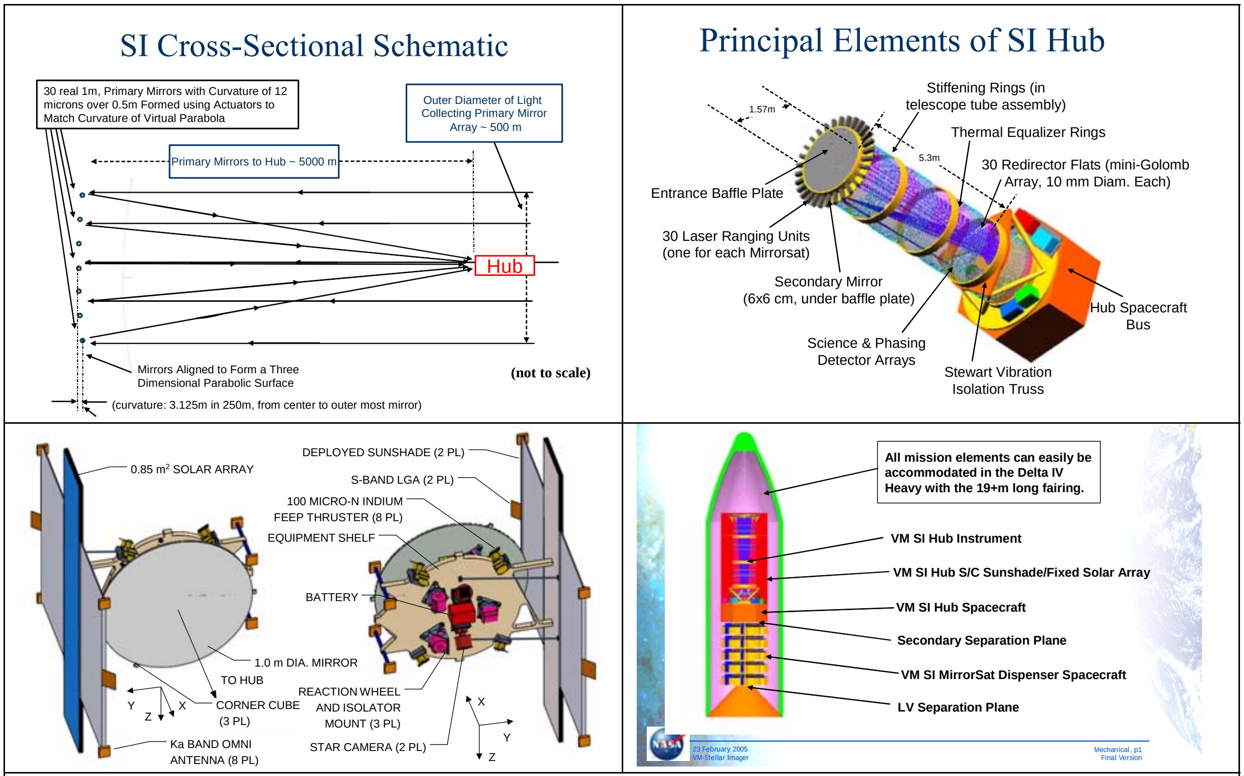


Figure 6: An overview of the VM SI Design, the details of the hub & mirrorsats, and one launch option.

Figure 6 (upper right) shows the beam-combining hub, which contains additional optics and the detector systems. Light from the source is reflected off the 30 mirrors in the primary array and relayed into the hub spacecraft. The hub spacecraft effectively controls metrology, pointing and wavefront control between each of the mirrorsats and between the mirrorsats and the hub, and ultimately constructs both the UV and visible light science imagery. The baseline hub consists of multiple subsystems (Figure 7) which include: spacecraft bus, telescope tube assembly, internal optics, entrance baffle plate, metrology subsystem, wavefront control subsystem (visible light) and science focal planes (visible & UV light). Broadband light initially enters the hub from the 30 primary mirrors through the entrance baffle plate. This plate contains 30 holes, one per optical beam and in the same pattern as the primary mirror array. Its purpose is to minimize the amount of background sky light from between the mirrorsats that enters the hub. If other (non-subset) patterns were to be used, the plates would need to be “active”, i.e. in that the number and placement of apertures would need to be commandable. After passing through the plate the light travels the length of the hub tube (~5.3 meters) and is incident on 30 redirector flats, each of which is 10 mm in diameter and also arrayed in a scaled version of the Golomb array pattern. These flats move in piston, tip and tilt to facilitate pointing, metrology and wavefront control. After reflection off the flats the light comes to focus at the field stop mask and travels to an ellipsoidal secondary mirror (SM) mounted on tip/tilt control actuators. The SM relays the beams to the focal plane instruments. The focal plane science package consists of 4 instruments: (i) UV science camera, (ii) Visible science camera, (iii) wavefront sensing camera, and (iv) a "light bucket" spectrograph (used in a mode where the light from all mirrors is directed through a single aperture for maximum spectroscopic sensitivity, at the expense losing imaging capability). The two science channels have, in this baseline design, filters wheels in front of the detectors to produce the desired bandpasses for the observations. Alternative designs are envisioned which could replace this filter + standard detector set with either energy-resolving detectors, or with a more complex optical system that re-maps the 2D distribution of the beams into a 1D non-redundant array, whose light is then dispersed orthogonally at every point to produce more complete spectral information.

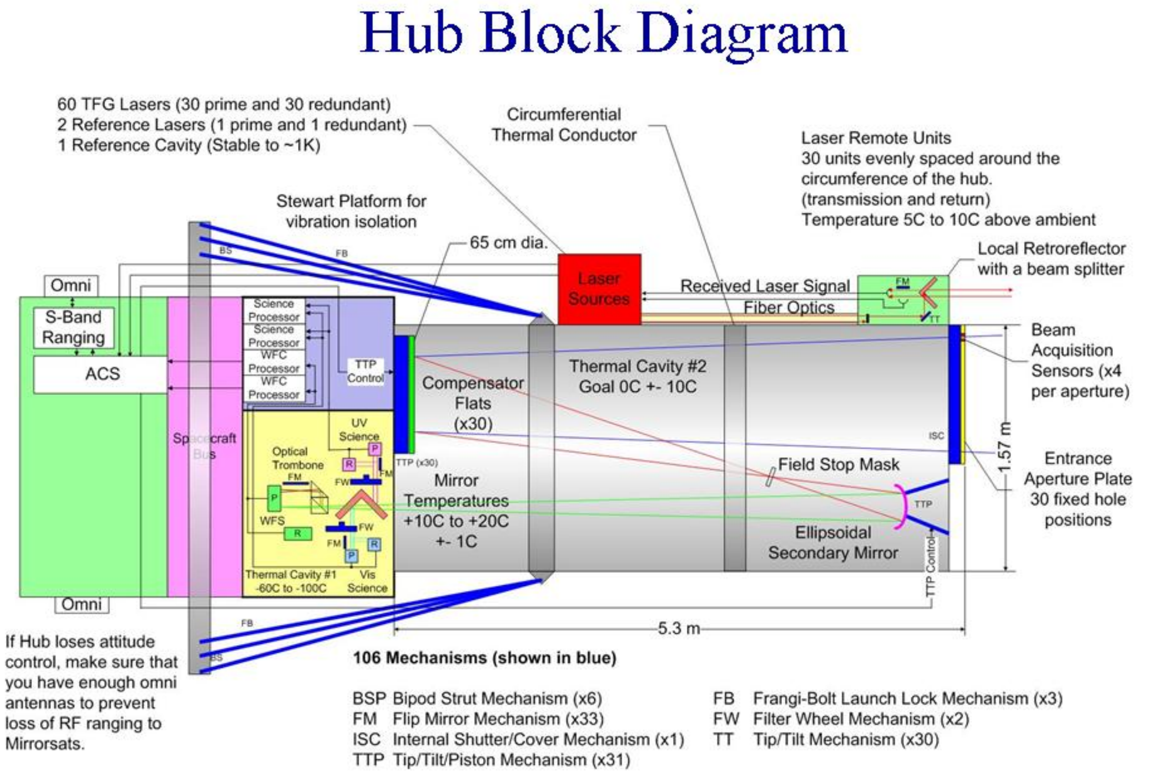


Figure 7: Details of one hub design ("light bucket" spectrograph not shown).

The beam combining hub is designed to be highly redundant at the component level. However, it is highly desirable from both a redundancy viewpoint and an operational efficiency viewpoint to actually launch and use in normal operations two identical hubs. With two hubs, one can be in motion while the other is being used for an observation, and thus "pre-positioned" for the next target. An alternative, of course, is to have available a second hub on the ground ready for a launch-on-need should a failure in the primary hub occur. This can enable a recovery from a hub failure, but at the cost of some down-time while the backup hub is launched and deployed at L2.

The individual mirrors in this design are fabricated as ultra-smooth, UV-quality flats, mounted on mirrorsats (Fig. 6-lower left) which are actuated to produce the extremely gentle curvature needed to focus light on the beam-combining hub that is located at the prime focus from 1 - 10 km distant. The focal length (distance of the hub) scales linearly with the diameter of the primary array, i.e., a 100m diameter array corresponds to a focal length of 1 km and a 1000m array to a focal length of 10 km. The "standard" configuration, in which a majority of the targets are likely to be observed, has a 500m array diameter and 5 km focal length. A one-meter primary mirror size is sufficient to ensure good signal/noise for the primary stellar activity targets. Sizes up to two meters may be considered in the future, depending on the breadth of science targets that *SI* is required to observe - e.g., some fainter extragalactic objects may need larger mirrors, but those will come at a cost to the packaging for launch, the number of launches needed, and total mission cost. The mirrorsats fly in formation with a beam-combining hub in a Lissajous orbit around the Sun-Earth L2 point. The satellites are controlled to within a mm-to-cm radial precision relative to the hub and the mirror surfaces to 5 nm radial precision, rather than using optical delay lines inside the hub for fine tuning the optical path lengths. This basic VM design can be launched on a single EELV, such as a Delta IV Heavy, Atlas V or other similar launch vehicle, as shown in Fig. 6 (lower right). Alternate design options are described in the SI VM Report.

SI will be transferred to a Sun-Earth L2 libration orbit using a direct transfer trajectory with a 120 day coast phase. Upon arrival and insertion into the mission orbit, a deployment of the components will begin. After initial check-out and commissioning, Stellar Imager will be an autonomously controlled constellation, with the frequency of re-pointing varying greatly, between once per hour, for surface imaging of the brighter stellar targets, and once per month during asteroseismology campaigns on individual stars. SI will survey multiple targets a day for 11 months/year and then dedicate ~1 month/year to the detailed, high-time resolution asteroseismic studies of select stars, which must be observed continuously for a stellar rotation period (days to ~1 month). SI will observe in a band ±20 deg from the orthogonal to the line to the Sun and will typically observe sequences of targets rather close together (slews of less than ~15 deg) to keep slew times to less than 1 hour. The hub will do most of the moving during re-targeting and the mirror array will be tilted to line up with the new direction to the hub. The MDL studies have indicated that there is no problem carrying sufficient propellant using Field Emission Electric Propulsion (FEEP) for small maneuvers and station-keeping and hydrazine thrusters for large maneuvers, given the VM Design Reference Mission. The Hub will contain the communications equipment for space-ground contact with the DSN and the mirrorsats normally will only talk to the Hub. The SI Mission and Science Operations Centers will be highly automated to minimize operational costs during the mission.

C. Technical Feasibility

Stellar Imager is part of a natural evolution from current ground-based interferometers and testbeds to a space-based system. The feasibility of interferometry and the phasing of small (<6 elements) sparse arrays has been demonstrated by the wide variety of optical and IR interferometers successfully operating or being built on the ground (e.g., CHARA, COAST, NPOI, MROI, and VLTI) and their performance can be improved by an increase in the number of telescope elements, just as it has been done at radio wavelengths (such as at the VLA/VLBA, Westerbork and Australia Telescopes). However, we note that space actually provides a better environment for interferometers – their performance on the ground is limited by having to look through an atmosphere, which limits spatial and temporal coherence (aperture size and integration time) of the incoming wavefront, and by the need for large and complicated delay lines to enable off-axis observations, since the array cannot be oriented normal to the incoming light from targets scattered over the entire sky. In space there is no atmosphere (limits on aperture size and integration time are greatly relaxed), the primary array can be tilted to enable on-axis observations of all targets (no need for numerous, complex, delicate, and expensive delay lines), and wavelengths (e.g. UV) can be accessed that cannot be seen from the ground. A direct imaging interferometer like SI is a logical first "large baseline space-based interferometer". It is easier to build than an astrometric interferometer like SIM, because its light-path delay tolerance is ~2 orders of magnitude less severe than SIM's λ/1000 level. It is also easier than missions like TPF-I, which aim at planet detection by nulling the central star, requiring a fringe contrast ~0.99999 and having error requirements which are ~10000x more severe than SI. A small-baseline space-interferometer with just a few primary mirrors, such as the NASA Fourier Kelvin Stellar Interferometer (FKSI) or ESA's Pegase, would be an ideal bridge from the ground-based to the large space-based interferometers.

D. Summary of SI Design Parameters

Table 1 summarizes the mission and performance parameters of the baseline SI design, with the specific items requested in the RFI set in boldface. Further information on tolerances etc. can be found in the SI VM Report.

Table 1: Mission and Performance Parameters from the VM Study

Parameter	**Value**	**Notes**
Maximum Baseline (B)	100 – 1000 m (500 m typical)	Outer array diameter
Effective Focal Length	1 – 10 km (5 km typical)	Scales linearly with B
Diameter of Mirrors	1 - 2 m (1 m currently)	Up to 30 mirrors total
λ-Coverage	UV: 1200 – 3200 Å Optical: 3200 – 6600 Å	Wavefront Sensing in optical only
Spectral Resolution	UV: 10 Å (emission lines) UV/Opt: 100 Å (continuum)	
Operational Orbit	**Sun-Earth L2 Lissajous, 180 d**	200,000x800,000 km
Operational Lifetime	5 yrs (req.) – 10 yrs (goal)	
Accessible Sky	Sun angle: $70^{\circ} \leq \beta \leq 110^{\circ}$	Entire sky in 180 d
Hub Dry Mass	1455 kg	For each of 2
Mirrorsat Dry Mass	65 kg (BATC design)	For each of 30
Ref. Platform Mass	200 kg	
Total Propellant Mass	750 kg	For operational phase
Total Mass to Orbit	**4355 kg**	
Anticipated Launcher	**Delta IV Heavy – 19 m fairing**	
Angular Resolution	50 μas – 208 μas (@1200–5000Å)	Scales linearly ~ λ/B
Typical total time to image stellar surface	< 5 hours for solar type < 1 day for supergiant	
Imaging time resolution	10 – 30 min (10 min typical)	Surface imaging
Seismology time res.	1 min cadence	Internal structure
# res. pixels on star	~1000 total over disk	Solar type at 4 pc
Minimum FOV	> 4 mas in single exposure	Larger via mosaic
Minimum flux detectable at 1550 Å	5.0 x 10^{-14} ergs/cm^{2}/s integrated over C IV lines	10 Å bandpass
Precision Formation Fly.	s/c control to mm-cm range	
Optical Surfaces Control	Actuated mirrors to μm-nm range	
Phase Corrections	to λ/10 Optical Path Difference	
Aspect Control/Correct.	3 μas for up to 1000 sec	Line of sight mainten.

III. Technology Drivers

The three major technology challenges to building SI are:

- **precision formation-flying of ~20-30 spacecraft** (including precision metrology over multi-km baselines and aspect sensing and control to 10's of micro-arcsec)
- **wavefront sensing and real-time autonomous analysis and closed-loop optical control of a many-element sparse array**
- **methodologies for ground-based validation of large-baseline many-element systems**

We discuss each of these three "tall poles" in further detail below.

A. Precision Formation Flying (PFF)

Probably the tallest pole among all these technologies is the precision formation flying (PFF) of as many as 31 distinct spacecraft: 30 mirrorsats and a beam-combining hub. This is a complicated, multi-stage controls problem. However, similar control systems will be needed for many future missions, e.g., all missions composed of distributed spacecraft flying in precise formations, so there is a great deal of motivation for such development.

PFF techniques must accommodate the deployment and initial positioning of elements in large formations and the real-time correction and control of those elements at the cm-to-mm level. This must be coordinated with the positioning of mirror surfaces on those spacecraft, for UV observations, to the 5nm level, which requires an overall system that works all the way from km → cm → nm scales. This will be done via autonomous staged-control systems which combine precision formation flying of spacecraft (the "mirrorsats" and the beam-combiner spacecraft) with precision active optical control of the mirror surfaces, i.e., their tip, tilt, piston, and translation. Metrology good to the 2-nm level must be enabled, if it is used alone for path length control, but that requirement can be relaxed to 0.5 microns if the system hands-off to a wavefront sensing & control system for the nm-level positioning. Individual spacecraft pointing is at the arcsec level, with mirror surfaces controlled separately, to 1.5 mas.

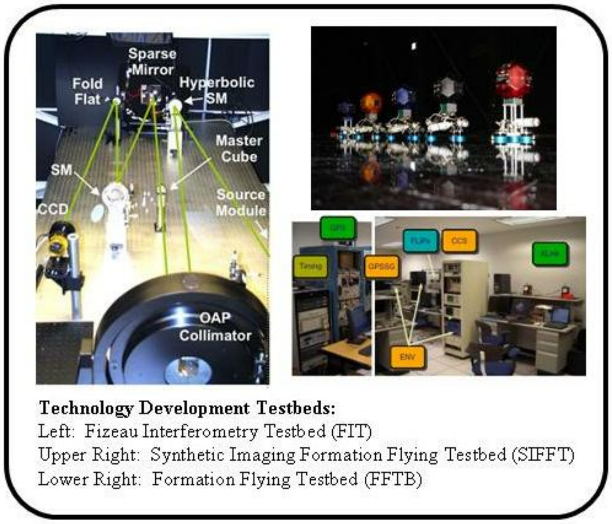
We continue to probe the best way to accomplish PFF of a many-element system, considering both free-flying spacecraft using thrusters such as Field Emission Electric Propulsion (FEEP) vs. electromagnetic formation flying (EMFF) vs. tethered concepts which would require fewer, but more mobile elements, using the MIT SPHERES (Synchronized Position Hold Engage Reorient Experimental Satellites) experiments (Mohan et al. 2007, *Proc. SPIE Conf.* #6687-40) and the GSFC Formation Flying Testbed (FFTB). This capability also requires the further development of precision metrology over long baselines (~km), for which efforts are underway at JPL (Lay et al. 2003, *Opt. Lett.* 28, 890) and SAO (Phillips et al. 2005, *Rev. Sci. Instr.*, 76, 064501).

Under the context of the New Millennium Program ST-9, the formation flying community was brought together to identify the critical capability requirements for PFF. A roadmap (see Carpenter et al. 2009 Decadal Technology Whitepaper) was developed by a cross-cutting team consisting of GSFC, JPL, AFRL, NRL, industry, and academia, to represent the progression of capabilities needed vs. rolled up formation flying capability (expressed in terms of formation control precision requirements) to enable distributed spacecraft missions like SI.

B. Wavefront Sensing and Closed-Loop Optical Control of Many-Element Sparse Arrays

Wavefront sensing and control, based on feedback from the science data stream, especially in the context of a very sparse aperture imaging system, needs continued long-term work. The Fizeau Interferometer Testbed (FIT; Fig. 8) is exploring this technology (Lyon et al. 2007, Proc. SPIE Conf. 6687-15) now with 7 elements and will expand to 18 elements, but it is a small effort that needs to be expanded to fully develop the needed algorithms and control laws. And it needs eventually to be integrated with a formation flying testbed, such as the GSFC FFTB or the MIT SIFFT/SPHERES experiments (Fig. 8) to develop and prove the staged-control laws needed to cover the full km-to-nm dynamic range (http://hires.gsfc.nasa.gov/si/aas_fit_sifft_poster_121206.pdf).

One of the more interesting technology options that is being pursued is an investigation of how much of the measurement and control job (of the various spacecraft and mirror surfaces in the distributed system) can be done purely by "external" (to the science data stream) metrology using, for example, lasers and at what point, and if, it will be necessary to handoff the measurement and control job to a system based on feedback from analysis of the science data stream. The "baseline" SI mission concept in fact assumes that the external metrology system has measurement and command authority down to the millimeter or, if possible, the micron level and that a "closed-loop" optical control system, based on phase diversity analysis of the science data stream, takes over at smaller scales to obtain control down to the nanometer level. The exact point at which that handoff occurs in the multi-stage control system will be addressed during the 2010 technology development effort. Our technology development plan is based on reducing risk by improving both technologies, i.e., by driving the external metrology to the smallest attainable scales and the wavefront sensing & control to the largest possible scales, so that the two systems will in the end have the largest possible overlap in their control authority.



Technology Development Testbeds:
Left: Fizeau Interferometry Testbed (FIT)
Upper Right: Synthetic Imaging Formation Flying Testbed (SIFFT)
Lower Right: Formation Flying Testbed (FFTB)

Figure 8: Ground-based testbeds are developing needed technology for SI, but need to be enhanced and extended.

This topic, as we mean it here, is a roll-up of multiple tasks, needed to bring the capability up to TRL-6, and includes: (a) the creation and coupling of thermal/structural/optical models with formation flying models for mirrorsats and hub (b) use of the model to develop parametric sensitivities, range, resolution, temporal bandwidths, accuracy, and precision requirements at the subsystem (mirrorsats & hub) and down to the component level, (c) use of the model, with noise (photon, read, dark), LOS jitter per mirrorsat and hub to simulate realistic focal plane data to assist in the developments, assessment, and comparison of heirarchical closed-loop sensing and control algorithms (which need to be cross-validated on the FIT and other testbeds to develop a model sufficient to predict the behavior of SI for target acquisition, coarse and fine phasing and software correction of the final image), (d) assessment of knowledge vs control, e.g. fringe tracking within a coherence length allows relaxation of control tolerances but not sensing tolerances, thus knowledge is high and it is subsequently used to 'software-correct' the final image, but when does this approach actually breakdown, i.e., how robust and viable is it ?

C. Integration and Test of Long-Baseline, Distributed Spacecraft Observatories

Finally, one of the most challenging technology needs for SI and all large, distributed spacecraft missions: *how does one test and validate on the ground, prior to flight a system whose components are numerous (~30) and whose separations in flight are order of 100's of meters to many kilometers?* This is also a critical need for, e.g., TPF-I/Darwin, LISA, Gen-X, BHI, LF, and PI. The likely solution is a combination of intense testing at the component level with extensive simulations of the system level performance. This type of I&T could include full-scale tests of a subset of the spacecraft at one time, perhaps suspended in the air and separated by up to 100's of meters, combined with sophisticated modeling to predict flight performance of the full constellation. Much work is required to identify the best approaches and to validate them using prototypes in a lab environment.

The technology challenges identified above have all been addressed prior to and during the SI Vision Mission (VM) study, in GSFC Integrated Design Center (IDC) studies over the period 2001-2005 and in other IDC studies run jointly with other missions. Credible and feasible approaches to the successful development of all these technologies were derived during the course of those studies and are documented in the SI VM Final Report, but these must be funded and implemented during the 2010 decade to enable the technologies to be ready for flight in the following decade (see also the Decadal Technology Whitepaper by Carpenter et al. 2009). The experiments mentioned above currently have no assurance they will be supported as long as needed and to the fine levels required. The development plan for these "tall pole" technologies and a number of other technologies that we perceive as easier to develop is summarized in Table 2. In addition, we strongly recommend the development and flight of one or more smaller interferometric missions, such as the Fourier Kelvin Stellar Interferometer (FKSI) or Pegase, in the mid-2010's as a logical way to progress to the large, strategic interferometric missions such as SI in the 2020's.

Table 2: Technology Roadmap for the Stellar Imager

Technology Needed by SI	Current TRL	Development Plan and/or Candidate Technologies	Readiness Date
Most Significant Challenges			
Precision Formation Flying of many-element arrays	3-4	SIFFT/SPHERES & GSFC Distributed Space Systems Roadmap	2014 for sm. missions 2018 for Great Obs.
Wavefront Sensing & Control and Closed-Loop optical path control of many-element sparse arrays	4	Fizeau Interferometry Testbed (FIT)	2013
Methodologies/control processes for ground-based I&T of distributed systems	2	GSFC Distributed Space Systems Roadmap (Figure 3.20 in full SI Report)	2016
Easier Challenges			
Aspect Control to 10's of μarcsecs	3	Trade external metrology vs. wavefront sen.	2018
Precision Metrology over long baselines	3	JPL & SAO metrology labs	2014
Mass-production of spacecraft (e.g., SI "mirrorsats")	4	TBD (but see BATC approach in section 3.18 of full SI Vision Mission Report)	2015
Lightweight, UV-quality mirrors with km-long radii of curvature	3	Chen et al. (2003, Proc. SPIE Conf. 4854, pp. 21-28)	2015
Methodologies for combining 20-30 simultaneous beams	4	Ground-based interferometers, FIT	2012
Variable, non-condensing μN thrusters	4	FEEPs, etc.	2013

IV. Activity Organization, Partnerships, and Current Status

The Stellar Imager Vision Mission concept is under development by NASA's Goddard Space Flight Center, in collaboration with a broad variety of industrial, academic, and astronomical science institute partners, as well as an international group of science and technical advisors as shown in Figure 9. If further development work is funded for SI, we envision an organization as shown in Figure 10 to execute that work. SI addresses science goals of both the NASA Astrophysics and Heliophysics Divisions. It is a candidate implementation of the UVOI in the 2006 Science Program for the Astronomy/Physics Division and a "Flagship and Landmark Discovery Mission" in the 2005 Heliophysics Roadmap. SI was the subject of a 2004-2005 NASA/HQ "Vision Mission" Study (see the SI VM Final Report), and has been recommended in the NRC Report (2008) for further study as a mission potentially enhanced by launch on an Ares V. Specific SI-related technology development efforts currently underway include the GSFC Fizeau Interferometry Testbed to develop closed-loop wavefront sensing and optical control of many-element sparse arrays and the MIT SPHERES experiments to develop and test formation flying algorithms. SI is targeted for launch in the mid-to-late 2020's, the decade after the one under consideration now, but significant technology development (above and beyond the modest efforts noted above) in the 2010's is needed to enable SI and other space-based, sparse aperture telescopes and interferometers to be flown in the following decade and beyond.

- Mission concept under development by NASA/GSFC in collaboration with experts from industry, universities, & astronomical institutes:

  Arizona State University
  Ball Aerospace & Technologies Corp.
  Marshall Space Flight Center
  National Optical Astronomy Observatory
  Northrop-Grumman Space Tech.
  Sigma Space Corporation
  Space Telescope Science Institute
  Stanford University
  University of Maryland

  European Space Agency
  Astrophysical Institute Potsdam

  Catholic University of America
  Lockheed Martin Adv. Tech. Center
  Massachusetts Inst. of Technology
  National Solar Observatory
  Seabrook Engineering
  Smithsonian Astrophysical Observatory
  State Univ. of New York/Stonybrook
  University of Colorado at Boulder
  University of Texas/Arlington&SanAn.

  College de France
  University of Aarhus

- Institutional and topical leads from these institutions include:
  - K. Carpenter, C. Schrijver, M. Karovska, A. Brown, A. Conti, K. Hartman, S. Kilston, J. Leitner, D. Lakins, A. Lo, R. Lyon, J. Marzouk, D. Miller, D. Mozurkewich, J. Phillips, P. Stahl, F. Walter
- Additional science and technical collaborators from these institutions include:
  - S. Baliunas, C. Bowers, S. Cranmer, M. Cuntz, W. Danchi, A. Dupree, M. Elvis, N. Evans, M. Giampapa, C. Grady, T. Gull, G. Harper, L. Hartman, R. Kimble, S. Korzennik, S. Kraemer, M. Kuchner, S. Leitch, M. Lieber, C. Lillie, J. Linsky, M. Marengo, K. Mighell, R. Moe, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, T. Rimmele, A. Roberge, D. Sasselov, S. Saar, E. Schlegel, J. Schou, P. Scherrer, W. Soon, G. Sonneborn, E. Stoneking, R. Windhorst, B. Woodgate. R. Woodruff
- International Partners include:
  - J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, A. Labeyrie

Figure 9: The SI Team - a broad collaboration of scientists & engineers.

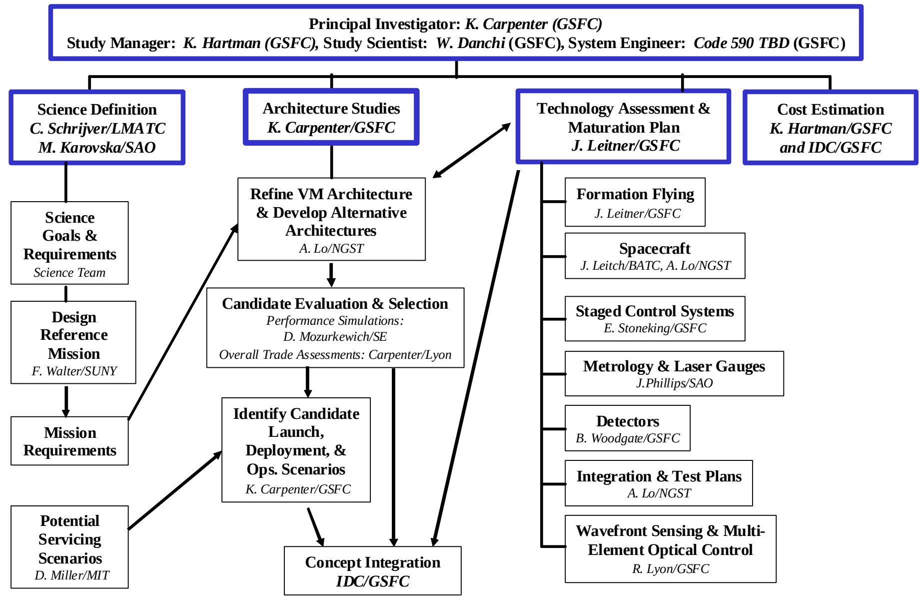


Figure 10: The SI Project organizes a broad talent base into efficient topical units.

V. Activity Schedule

Since the activity to be accomplished in the 2010 decade, and thus of the most interest to the current Decadal Survey Team, is the technology development needed to enable flight for SI in the latter part of the following decade, we show here schedules both for this nearer term technology development and for the active mission phases as well. Section III and Table 2 summarized both the "tall poles" and the easier technology efforts that need to be pursued in the coming decade to enable SI in the decade of the 2020's and provided approximate "readiness dates" for each technology. In Figure 11 we show the schedule for the "tall pole" technologies alone, with the Precision Formation Flying broken into two segments, one for small baseline distributed systems with a few elements and one for the full-up SI design with 30 or more distinct spacecraft over km-length baselines. We believe it is in these areas that investments should be concentrated to enable SI and other long-baseline interferometers and sparse aperture telescopes in the following decade. We will include cost estimates for these activities in the following section.

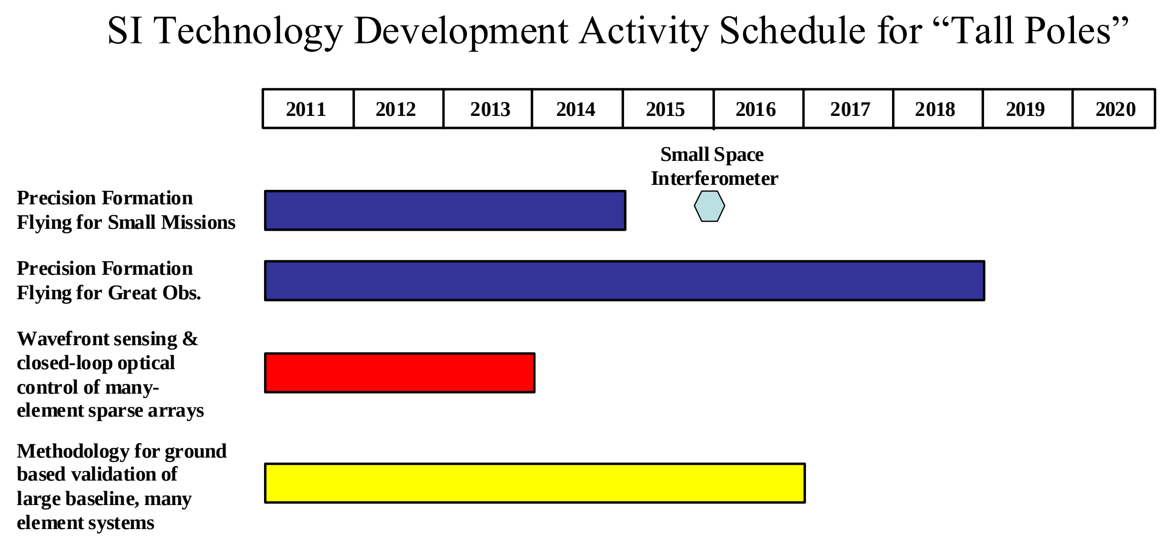


Figure 11: Technology Development Schedule for the most challenging items needed for SI. All of these critical items can be developed readily within the coming decade, with suitable investments beginning in 2011.

The schedule for the SI mission itself that is assumed for the following costing estimate is shown in Figure 12. We show the mission development schedule in terms of Years from Phase A start, since the start point is very uncertain. We do, for purposes of illustration, put two sets of tentative dates at the top of Figure 12, showing both a "sooner" and a "later" option. A Phase A start in 2016, followed by a 2024 launch, can be supported by the technology plan. However, a Phase A start in 2021 leading to a launch in 2029 seems more realistic, so we show that as well. The phasing is the same in both cases, with an 8 year development period, followed by a minimum 5 years of mission operations, with a 10 year mission as a goal. A six-month cruise and calibration period to the L2 operational orbit is included. Phase A is assumed to last 1 year, phase B 2 years, and phase C/D 5 years. The high-level project milestones as required in NASA Procedural Requirements (NPR) 7120.5D are also shown: Formulation Authorization, Mission Design Review (MDR), Preliminary Design Review/Non-advocate Review (PDR/NAR), System Integration Review (SIR), Flight Readiness Review (FRR), and the Launch Readiness Review (LRR).

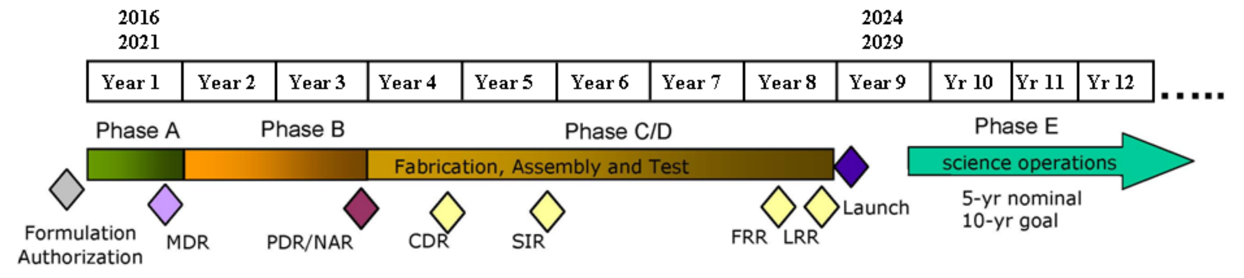


Figure 12. The SI Mission Schedule assumed for the costing exercise in Section VI.

Prior to this notional start date, however, there is a strong need for technology development as described above and in the Technology Whitepaper "*Technology Development for Future Sparse Aperture Telescopes and Interferometers in Space*" submitted to the Decadal Survey by Carpenter et al. (2009). That technology development effort is being pursued at modest levels now and should be expanded in the early years of the 2010 Decade, as shown above, to support launch readiness dates in the last half of the 2020 decade.

VI. Cost Estimates

We provide two costs estimates in this section: one for the technology development activities which we recommend be pursued in the decade of the 2010's and one for the actual mission costs assuming SI is launched in the second half of the 2020 decade.

The technology development costs are estimated (in constant 2009 $'s) based on experience-to-date with the on-going efforts in each area, although we would recommend that a peer-review process actually be used to select and determine the precise amounts required to ensure the work can be accomplished on the stated time scales. Here we provide approximate costs for the three "tall pole" technologies that need to be developed and suggest some additional funding needed to ensure the "easier" technical challenges are also addressed.

We estimate the total cost over the full decade of the technology work described above, excluding the "small space interferometer", at ~$37 M. A small space interferometer like FKSI is likely to be a "probe class" mission and cost ~$635 M (Danchi et al. FKSI RFI Response).

These costs were derived as follows. The cost of the precision formation flying development was estimated assuming a work plan as outlined in the GSFC Distributed Systems Roadmap and supported by future experiments with the MIT SPHERES and GSFC Formation Flying Testbeds, which requires on the order of $1.5 M per year from 2011-2018 ($12 M total). The wavefront sensing & control tasks listed in Section III plus the system-wide modeling needed to assist I&T preparations will require ~12.5 FTE's spread out over 4 - 5 years, i.e., about $3M for personnel. In addition, testbed hardware and integration with all electronics, actuators, optics and control algorithms are likely to exceed ~$3M but it is hard to provide a precise figure without a full design effort. Finally, the costs of a long term facility in which to build these experiments up and operate them need to be covered. We thus estimated a total of ~$7 M for the wavefront sensing, optical control, and system modeling tasks. Development and validation of procedures for ground-based Integration & Test of many-element, widely distributed systems is envisioned to take about 6 years if started in 2011 and to cost approximately $ 500 K per year, for a total of $3 M. These primary technology development tasks thus total ~$ 22 M over the decade. If, in addition, we allocate ~$1.5 M/yr over 10 years, to cover the "easier" tasks, plus the run out of some of the above tasks to the end of the decade, then a grand total for the technology work, exclusive of the "small space interferometer", comes to the $37 M given above for the decade.

Since the SI mission is in the early stages of conceptualization, the cost estimates for it are necessarily less robust than for mission to be flown in the near future. However, we have over the last 8 years performed a number of design studies in the GSFC Integrated Design Center (IDC), including both the Mission Design Lab (MDL) for the overall mission, and the Instrument Design Lab (IDL) for the beam-combining hub and the science payload. NASA also commissioned a "Vision Mission (VM)" Study of SI in 2004-2005, which developed a detailed design that meets the performance requirements required to achieve the SI science goals. These studies involved experts from a full range of technical disciplines, including power, guidance & navigation, flight dynamics, operations, communications, quality assurance, system engineering, etc., and cost estimation. The MDL worked on the overall design of a space-based Fizeau interferometer, located in a Lissajous orbit around the sun-earth L2 point, while the IDL concentrated its efforts on the design of the beam-combining hub in the context of the selected overall architecture. These studies explored the technical feasibility of the mission, identified the technology developments needed to enable the mission in the 2024+ timeframe, and provided cost estimates as described below.

We have used both Parametric and Analogous methods to estimate the cost of the SI mission. Parametric Cost Modeling at GSFC includes the use of PRICE-H (Hardware) and/or SEER-H (Hardware) for mission hardware cost estimating. The MDL at the time had 7+ years experience with 100+ Bus models, while the IDL had 5+ years experience with 50+ Instrument models, and GSFC Code 605 had 7+ years experience with 40+ S/C Bus and 40+ Instrument models. All recent GSFC Discovery, Mars Scout, and SMEX proposals were/are estimated with PRICE-H and SEER-H. The Analogous cost methodology is based on historical data and involves comparison and extrapolation to like items or efforts in previous missions and design efforts.

We first considered the costs of the mirrorsats and beam-combining hub, using both Price-H and the JSC mass-based Advanced Missions Cost estimator (http://cost.jsc.nasa.gov/AMCM.html). Costs based on Price-H from the GSFC IDC sessions were used and inflated to 2009$. The mirrorsats were studied during 2001, the hub spacecraft in 2004, and the payload in 2005. Second, the spacecraft/vehicle level mass-based cost estimator from the JSC web site (http://cost.jsc.nasa.gov/SVLCM.html) was used assuming the parameters shown in Table 3. We also compare in Table 3 the cost estimations for the mirrorsats and hub/payload. Inflating the JSC 2004$ estimates to 2009$ gives $1.5B which is approximately 36% higher than the $1.1B cost for mirrorsats and hub/payload based on Price-H estimates. The Price-H estimates were used in the total mission cost derived below, since they were generated using estimates of specific hardware component costs and we believe them to be more reliable.

Table 3. Cost Comparisons for Mirrorsats and Hub/Payload ('09$)

Component	Price-H/IDC	JSC Estimator (avg. complexity)	Assumptions
30 Mirrorsats	$656M	$759M	65 kg each
One Payload Hub	$466M	$767M	1455 kg
Component Total	$1.1B	$1.5B	

Project management, mission systems engineering, mission assurance, and system integration and testing are estimated as percentages of hardware costs based on cost averages from the extensive GSFC mission flight experience. Science costs in Phases C/D are based on $500K per instrument per year for a flagship mission class, while Phase E is scaled from HST, accounting for fewer discrete targets and programs/year. Four instruments are included: UV and visible cameras, a wavefront sensing and control system, and a “light bucket” spectrograph, which are costed based on HST experience. In Phase E, $ 15 M/year (of line 4.0) goes directly to the astronomical community in the form of grants. Reserves are computed as 30% of Phase B-E cost before adding the launch vehicle cost. EPO costs are based on appropriate levels for a Flagship mission. For purposes of costing an EELV, we randomly selected the Delta-IV Heavy, whose cost was estimated from information on the Astrophysics Strategic Mission Concept Studies (ASMCS) workshop webpage, i.e., 4.2 times the cost of a small launch vehicle ($160M in 2015$), and deflated to 2009$. The estimate for the cost of a Delta IV Heavy launch listed there is thought to be high, but is left as is for consistency with the proposal instructions given for the recent Astophysics Strategic Missions Concept Studies. The SI hardware can be accommodated in other launch vehicles with similar characteristics.

The process above yields a total mission cost in 2009$ of $2.9B. The breakout and methodologies used to estimate this mission cost are shown in Table 4.

Table 4: SI Mission Cost Estimate ($ M, 2009) and Methodology - updated 3/23/09

Cost Element	**Phase A**	**Phase B**	**Phase C/D**	**Dev Total**	**Phase E**	**Mission Total**	**Cost Methodology**
Project Elements:							
1.0 Project Management	2	9	91	102	9	**111**	9% hardware costs B-D;9% of Mission Ops
2.0 Mission Sys Engr	2	8	81	92	8	**100**	90% of Project Mgmt
3.0 Mission Assurance	2	3	33	38	3	**41**	40% of Systems Engineering
4.0 Science	2	3	6	11	129	**140**	Based on Flagship mission data; analogous ops costs
5.0 Payload & SC	5	52	409	466	0	**466**	MDL and IDL estimates, Price-H
6.0 Flight Systems (incl. 30 mirrorsats)	6	52	598	656	0	**656**	MDL and IDL estimates, Price-H
7.0 Mission Ops	1	4	15	21	103	**124**	MDL estimates; analogous cost, and cost calculators
9.0 Ground System	2	2	2	6	10	**16**	MDL estimates; and analogous cost
10.0 System I&T	1	10	101	112	0	**112**	10% of hardware costs
Sub total	**24**	**143**	**1336**	**1504**	**263**	**1766**	
Reserves	0	43	401	444	64	**508**	
Sub total w/reserves	**24**	**186**	**1737**	**1948**	**327**	**2273**	
Elements w/o cont:							
8.0 Launch Vehicle	0	0	571	571	0	**571**	Delta IV H cost from ASMCS webpage;deflated to '09$
11.0 E/PO	0	3	12	15	15	**31**	Phase B-E, appropriate levels for Flagship mission
Mission Total:	**24**	**190**	**2320**	**2534**	**342**	**2875**	

VII. Summary

We have described the breakthrough science that can be obtained with a large-baseline, space-based spectral-imaging UV/Optical interferometer like Stellar Imager (SI), including studies of: 1) dynamos and magnetic activity in the Sun & stars and their role in the formation and evolution of stars and in the habitability of planets, 2) mass transport processes and their roles in the formation, structure, and evolution of stars and stellar systems, and 3) Active Galactic Nuclei and their role in galaxy formation and evolution (see the Decadal Survey science whitepapers by Schrijver et al. (2009), Carpenter et al. (2009), and Kraemer et al. (2009), respectively). It will, as part of its mission, characterize the central stars of nearby exo-planetary systems and assess their impact on the habitability of surrounding planets. In fact, SI will address a broad range of astrophysical problems and be a powerful resource for the entire astronomical community. SI complements UV/optical mission concepts like ATLAST (which use 8-16m mirrors to obtain high sensitivity over large fields of view) by using a large, sparse array, with an angular resolution *60-125x greater,* to zoom in and observe the detailed structure of targets and resolve the dynamic motion of material within and between those targets.

The sub-mas observations needed to enable this breakthrough science can only be provided by long-baseline interferometers or sparse aperture telescopes in space, since the aperture diameters required are in excess of 500 m – a regime in which monolithic or segmented designs are not and will not be feasible - and since they require observations at wavelengths (UV) not accessible from the ground. The SI is a logical step in the quest for higher spatial resolution, following-on from HST in space and from AO on the ground, taking it to regimes not possible with either.

The technology developments needed for these missions are challenging, but eminently feasible (Carpenter et al. 2009 Decadal Technology Whitepaper) with a reasonable investment over the next decade to enable flight in the 2024+ timeframe. That investment would enable tremendous gains in our understanding of the individual stars and stellar systems that are the building blocks of our Universe and which serve as the hosts for life throughout the Cosmos, as well as a broad range of general astrophysics enabled by this dramatic leap in angular resolution.

The SI Team has executed an ~1.5 year "Vision Mission" study (summarized by Carpenter et al. 2008, in *NASA Space Science Vision Missions*, ed. M. Allen, *Progress in Astronautics & Aeronautics,* vol. 224, pp. 191-227; the full report is available on the SI website) to develop in detail the scientific goals and requirements of the mission, a baseline observatory architecture, the technology development needs of that and alternative architectures, a roadmap for that technology development, considered deployment and operations scenarios and addressed operations assurance and safety issues. That study has shown that the scientific capabilities of such an ultra-high angular resolution UV/Optical interferometer are extraordinary, that credible design options are available, and that a sensible technology development path for supporting the development of the facility can be defined for the decade of the 2010's. SI fits well with the NASA and ESA strategic plans and complements other defined and conceptual missions, such as TPF, LF, and PI, and supports our collective desire as a species to understand other stars, extra-solar planetary systems and the habitability of surrounding planets, as well as improve our understanding of our own sun and its impact on earth's climate and it's future habitability.

Additional information on the Stellar Imager can be found at *http://hires.gsfc.nasa.gov/si/*