

****FULL TITLE****
*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***
****NAMES OF EDITORS****

The *Stellar Imager (SI)* - A Mission to Resolve Stellar Surfaces, Interiors, and Magnetic Activity

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Abstract. The *Stellar Imager (SI)* is a UV/Optical, Space-Based Interferometer designed to enable 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and, via asteroseismology, stellar interiors and of the Universe in general. The ultra-sharp images of the *Stellar Imager* will revolutionize our view of many dynamic astrophysical processes by transforming point sources into extended sources, and snapshots into evolving views. *SI*'s science focuses on the role of magnetism in the Universe, particularly on magnetic activity on the surfaces of stars like the Sun. *SI*'s prime goal is to enable long-term forecasting of solar activity and the space weather that it drives. *SI* will also revolutionize our understanding of the formation of planetary systems, of the habitability and climatology of distant planets, and of many magneto-hydrodynamically controlled processes in the Universe. *SI* is included as a "Flagship and Landmark Discovery Mission" in the 2005 NASA Sun Solar System Connection (SSSC) Roadmap and as a candidate for a "Pathways to Life Observatory" in the NASA Exploration of the Universe Division (EUD) Roadmap (May, 2005). In this paper we discuss the science goals and technology needs of, and the baseline design for, the *SI* Mission (<http://hires.gsfc.nasa.gov/si/>) and its ability to image the Biggest, Baddest, Coolest Stars.

1. Introduction

The *Stellar Imager (SI)* is a NASA Vision Mission (VM), designed to study 1) solar and stellar magnetic activity and their impact on space weather, planetary climates, and life and 2) magnetic processes in general and the roles they play in the origin and evolution of its structure and the transport of matter throughout the Universe. *SI* has been in the NASA Sun-Earth Connection (SEC) / Sun Solar System Connection (SSSC) / Heliophysics Science Division (HSD) Roadmaps since the year 2000. It is being developed by NASA/GSFC in collaboration with a broad set of institutions and individuals assembled for the VM

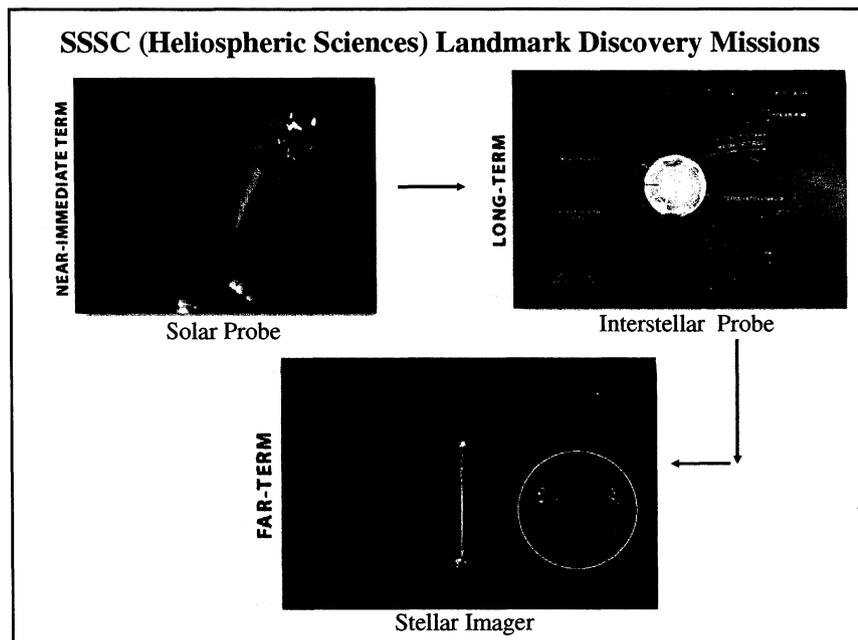


Figure 1. "Landmark Discovery (aka, "Flagship") Missions" included in the 2005 NASA SSSC/Heliophysics Division Roadmap. *Stellar Imager* is the ultimate component of that sequence.

Study in 2004-2005, who continue to develop the science goals, architectural designs, and the needed technologies. *Stellar Imager* is included in the 2005 Heliophysics Roadmap as a Flagship (Landmark Discovery) mission (see Figure 1) and is also a candidate "Pathways to Life Observatory" in the 2005 Exploration of the Universe Division (EUD), now the Astrophysics Division, Roadmap. The *SI* Team is also working with the ESA "Luciola" Cosmic Vision Team (P.I. Antoine Labeyrie) to take advantage of synergies that might be available due to the overlapping science goals and technology needs of the two missions.

SI's primary science goal will be addressed by observing and measuring spatial and temporal stellar surface magnetic activity patterns through ultra-high angular resolution (≤ 0.1 milli-arcsec) UV imaging, and by measuring via disk-resolved asteroseismology the internal structure and flows that produce it, in a sample of stars covering a broad range of masses, radii, and activity levels. These observations will lead to an improved understanding of the underlying dynamo process(es) and thus enable improved forecasting of solar (and stellar) activity on time scales of days to centuries. This, in turn, will facilitate an improved understanding of the impact of stellar magnetic activity on life on earth and on exo-planets found around more distant stars. *SI* will enable a complete assessment of external solar systems by imaging the central stars of systems for which the IR-interferometry missions (*TPF*, *IRSI/Darwin*, *PI*) find

and image planets, and by determining the impact of the activity of those stars on the habitability of the surrounding planets.

An observatory with *SI*'s capabilities will also open a major new "discovery space" for astrophysics in general by providing a factor of more than 200x increased angular resolution in the UV/Optical over that available with the *Hubble Space Telescope (HST)*. This improved angular resolution, coupled with the spectral energy information *SI* will provide, will enable the resolution of the central regions of active galactic nuclei, supernovae and planetary nebulae, the mass-flow in interacting binary systems, and of the extended atmospheres and winds of cool, evolved giant and supergiant stars. At these resolutions, sequences of images will reveal the dynamics of astrophysical processes and allow us to directly see, for the first time, the evolution of, e.g., a planetary nebula, an early supernova phase, mass exchange in binaries, (proto-)stellar jets, and accretion systems in action.

The detailed results of the *SI* VM Study, including science goals, architecture concepts, and a technology roadmap, are available in the *SI* VM Final Report at <http://hires.gsfc.nasa.gov/si/>. In this paper, we summarize that material and present updates where available, as well as talk more specifically about *SI*'s ability to image the "Biggest, Baddest, Coolest Stars" that are the theme of this meeting.

2. Key Questions

There are a number of important questions that *SI* needs to address in order to achieve its goal of understanding dynamos and magnetic activity, including:

- what do the internal structure and dynamics of magnetically active stars look like?
- what sets the dynamo strength and pattern in individual stars, from dwarfs to supergiants?
- how can active stars form polar spots?
- what can we expect next from the Sun, on time scales from hours to centuries?
- why do 2 in 3 Sun-like stars show no cycles?
- what causes solar-type 'Maunder minima' or 'grand maxima'?
- how does stellar activity drive all aspects of "space weather" and affect planetary climates and life around solar-type and evolved stars?
- how do dynamos evolve with time?
- how do dynamos differ in dwarf vs. giant stars?
- can we generalize stellar dynamo properties to more exotic objects such as interacting binaries or AGN's?

Only with the answers to such questions will it be possible to more fully constrain theoretical dynamo models and enable true forecasts of future solar and stellar magnetic activity. These questions will be addressed by spatially resolving stellar disks to map evolving atmospheric activity as a tracer of dynamo patterns and by asteroseismic probing (to at least degrees of order 60) of internal stellar structure and flows in stars of various masses, radii, and activity levels. Such a “population study” will provide answers far more rapidly than by continuing our close-up observations of the Sun over many decades as we observe it move through the multiple and different activity cycles that are needed to obtain a full set of observational constraints - and some of this data would never be obtainable from the Sun alone, as it is only one example of how dynamos operate and magnetic activity is produced.

An understanding of how stellar dynamos work will, in turn, provide a major stepping stone toward deciphering magnetic fields and their roles in more exotic, complex, and distant objects.

3. SI Requirements and an Architectural Concept

3.1. Design Requirements

The science goals of *SI* require that it have the following capabilities:

- Wavelength coverage: 1200-6600 Å
- access to UV emission lines from Ly-alpha 1216 Å to Mg II 2800 Å for stellar surface imaging
 - Important diagnostics of most abundant elements
 - much higher contrast between magnetic structures and background
 - smaller baselines (UV save 2-4x vs. optical, active regions 5x larger)
 - $\sim 10\text{-}\text{\AA}$ UV pass-bands, to isolate, e.g., C IV (100,000 K) & Mg II h&k (10,000 K)
- broadband, near-UV or optical (3,000-10,000 K) for high temporal resolution spatially-resolved asteroseismology to resolve internal structure
- angular resolution of 50 micro-arcsec at 1200 Å (120 mas @2800 Å)
- ~ 1000 pixels of resolution over the surface of nearby (~ 4 pc) dwarf stars and over the surface of the many giant and supergiant stars within ~ 2 kpc.
- enable energy resolution/spectroscopy of detected structures
- a long-term (~ 10 year) mission to study stellar activity cycles: individual telescopes/hub(s) must be able to be refurbished or replaced

3.2. "Strawman" Mission Architectural Concept

The Vision Mission Study developed a baseline mission design, shown in Figure 2, that satisfies all of the above requirements. This design is for a space-based, UV-Optical Fizeau Interferometer with 20-30 one-meter primary mirrors, mounted on formation-flying "mirrorsats" distributed over a parabolic virtual surface whose diameter can be varied from 100 m up to as much as 1000 m, depending on the angular size of the target to be observed.

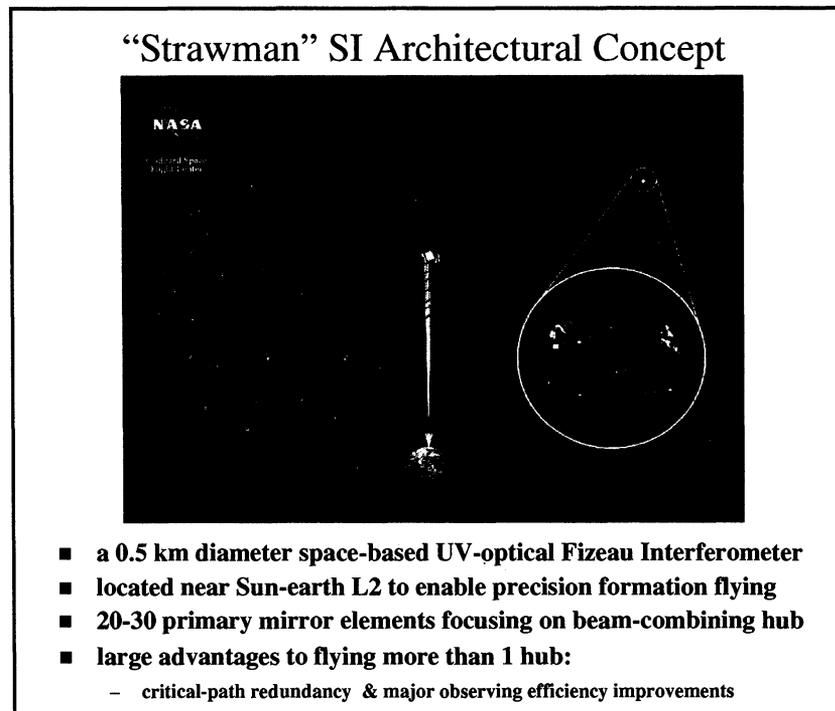


Figure 2. A summary of the current baseline *SI* architecture, with an artist's illustration on top and the basic characteristics of the observatory listed below.

The individual mirrors are fabricated as ultra-smooth, UV-quality flats and 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 scales linearly with the diameter of the primary array, i.e., a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array to a focal length of 10 km. The typical configuration has a 500 m array diameter and 5 km focal length.

A one-meter primary mirror size was chosen to ensure that the primary stellar activity targets can be well observed with good signal/noise. 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 mm-micron 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. A second hub is strongly recommended to provide critical-path redundancy and major observing efficiency enhancements. The observatory may also include a “reference craft” to perform metrology on the formation, depending on which metrology design option is chosen.

The VM Study identified two launch concepts that are quite feasible, assuming 1m diameter primary mirrors, with current vehicles. Depending on the number of hubs to be launched initially, one or two Delta IV launches will suffice to lift the entire observatory to Sun-Earth L2. If larger mirrors are decided upon, then either more launches will be needed or the new Ares V launcher being built for the moon-Mars initiative could perhaps be used.

Additional details on the architectural concept can be found in Carpenter et al. (2006b) and in the complete VM report at <http://hires.gsfc.nasa.gov/si/>.

4. What Will The *Stellar Imager* See?

The angular resolution of *SI* will enable us to see, e.g.: 1) **the signatures of magnetic activity on stellar surfaces** (e.g., typically-sized active regions on a Solar-type star at 4pc), as well as probe **stellar internal structure and flows** via high-time resolution asteroseismic disk-resolved imaging, 2) **infant star/disk systems** - accretion foot-points, the magnetic field structure and star/disk interaction, 3) **hot stars** - hot polar winds, non-radial pulsations and the envelopes and shells of Be-Stars, 4) **cool, evolved giant and supergiant stars** - spatiotemporal structure of extended atmospheres, pulsation, winds, and shocks, 5) **supernovae & planetary nebulae** - close-in spatial structure and evolution, 6) **interacting binary systems** - direct images of mass-exchange, dynamical evolution and accretion, and 7) **AGN** - transition zone between Broad and Narrow Line Emitting Regions and the origin & evolution of jets.

It is possible to simulate some of these views using theoretical models of these objects or phenomena as input to a simulator program written by Rajagopal et al. (2003). Figure 3 shows a variety of observations, including the surface and interior of a solar type star at 4pc, the magnetospheric-disk interaction region of a forming star, and the resolution of AGN Broad Emission Line Regions (BELR) geometries and inclinations. Figure 4 shows models of Betelgeuse and Mira at distances ~ 0.2 kpc and simulations of how those models would appear through a 2.5m telescope like *HST* (the Betelgeuse simulation is remarkably similar to actual *HST* observations). Figure 5 shows *SI* views of a Betelgeuse-like star at 2 kpc as observed with 25, 150, and 500m baselines (Note: more than 30 (spectral class>G5, Vmag<5, luminosity class higher than II) supergiants are thus readily accessible to *SI*.) Figure 6 shows simulations of a Mira-like star at 2 kpc viewed with 250 and 500 m baselines, respectively.

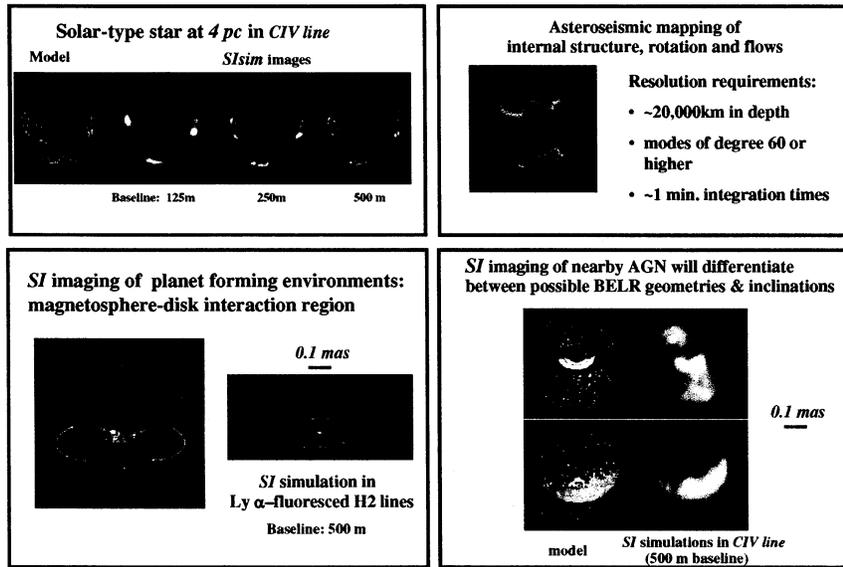


Figure 3. Simulations of observations that will be possible with *SI* at various wavelengths and baselines, computed with SISIM (Rajagopal et al. 2003).

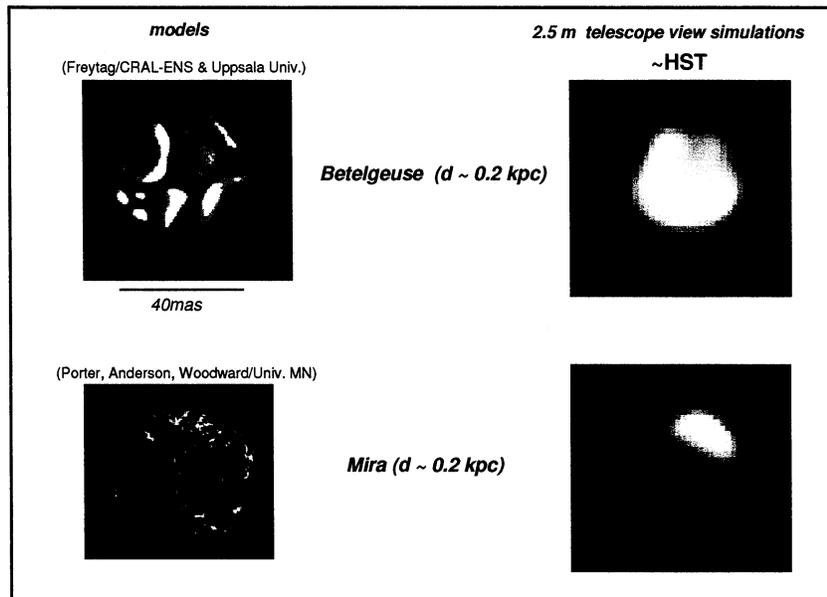


Figure 4. Models of Betelgeuse and Mira and simulations of what they would look like through a 2.5m telescope list *HST*.

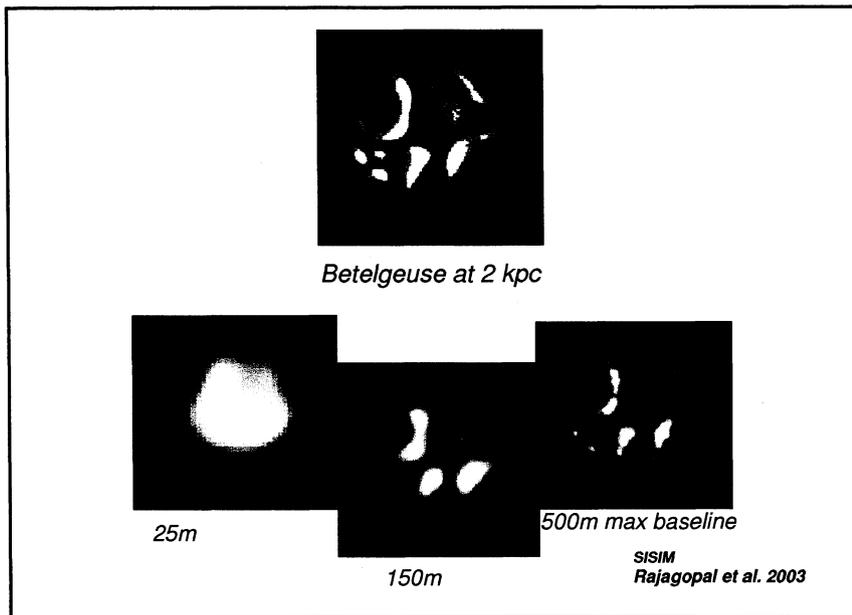


Figure 5. The Betelgeuse model, along with simulations of what *SI* would resolve with maximum baselines of 25m, 150m, and 500m, if the star were located at a distance of 2 kpc. The convective cells of red supergiants due to their enormous size can be readily observed by *SI* at such distances.

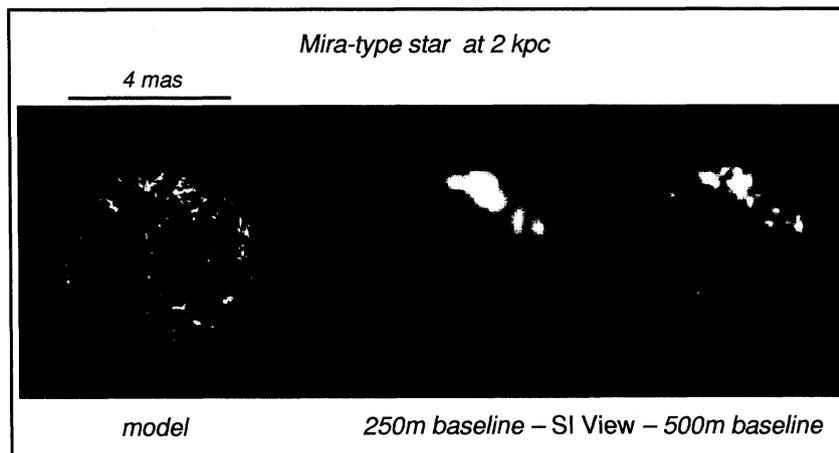


Figure 6. Simulations of *SI* observations of a Mira-type star at 2 kpc, with 250m and 500m maximum array baselines.

5. Technology Challenges and a Roadmap to Solving Them

The major technology challenges to building *SI* are:

- formation-flying of 30 spacecraft
 - deployment and initial positioning of elements in large formations
 - real-time correction and control of formation elements
 - staged-control system (km \rightarrow cm \rightarrow nm)
 - aspect sensing and control to 10's of micro-arcsec
 - positioning mirror surfaces to 5 nm
 - variable, non-condensing, continuous micro-Newton thrusters
- precision metrology over multi-km baselines
 - 2nm if used alone for pathlength control (no wavefront sensing)
 - 0.5 microns if hand-off to wavefront sensing & control for nm-level positioning
 - multiple modes to cover wide dynamic range
- wavefront sensing and real-time, autonomous analysis and control
- methodologies for ground-based validation of distributed systems
- additional challenges (perceived as easier than the above)
 - mass-production of “mirrorsat” spacecraft: cost-effective, high-volume fabrication, integration, & test
 - long mission lifetime requirement
 - light-weight UV quality mirrors with km-long radii of curvature (using active deformation of flats)
 - larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)

The major challenges in this list are being attacked via a number of ground-based testbeds (Carpenter et al. 2006a) to develop and assess precision (to the cm level) formation flying algorithms and closed-loop optical control of tip, tilt, and piston of the individual mirrors in a sparse array, based on feedback from wavefront analysis of the science data stream. The *GSFC Fizeau Interferometer Testbed (FIT)* is developing closed-loop optical control of a many-element sparse array, with 7-elements in Phase 1, and 18-elements in Phase 2. GSFC, MIT, and MSFC are collaborating on an experiment, the *Synthetic Imaging Formation Flying Testbed (SIFFT)*, utilizing the MIT SPHERES hardware on the MSFC Flat Floor facility to test cm-level formation flying algorithms. The *GSFC Formation Flying Testbed (FFTB)* is a software simulation facility that has been used to develop deployment of array spacecraft and the multi-stage acquisition of target light from the individual mirrors by the beam-combiner. In addition, there are relevant high precision metrology development efforts at

SAO (Phillips & Reasenberg 2005) and JPL (Lay et al. 2003). The ultimate goal of all these efforts is to demonstrate staged-control methodologies covering over 12 orders of magnitude, from km down to nm scales.

We are also studying alternative optical designs for *SI* to optimize its imaging and spectral energy resolution capabilities (Mozurkewich, Carpenter, & Lyon 2007).

The results from these testbeds and studies will be combined with experience from existing ground-based interferometers, such as *CHARA*, *NPOI*, *COAST*, and *MRO*, to enable a small, space-based UV/Optical Pathfinder mission, which will use a small number of elements (3-5) with smaller baselines (20-50m) and frequent array reconfigurations (to fill in the Fourier uv-plane and enable high quality imaging) to both accomplish important new science and demonstrate in space the technologies needed for the full-up *SI*. Such a Pathfinder mission could be flown as part of an Origins Probe program and launched in the 2015 time frame.

One or more such Pathfinder missions (others are possible in the IR and X-ray as pathfinders for *MAXIM/Black Hole Imager (BHI)* and the *Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS)*) will lay the ground-work for the long-baseline, Strategic “Vision” Missions that will do true high angular resolution interferometric imaging, including *SI*, *BHI*, *SPECS*, *Life Finder*, and *Planet Imager*).

6. Current Status of *SI*

SI is a strong candidate for a future NASA Strategic Mission, given its importance as a Landmark Discovery Mission in the Heliophysics Sciences Division Roadmap and its tremendous potential for cross-theme interest in the Astrophysics Division. The full-up mission is not likely to fly any sooner than the 2024 timeframe, though a smaller “pathfinder” mission could fly as an “Origins Probe” a decade earlier and do both significant science and technology demonstration. The GSFC Integrated Design Centers have done detailed studies and produced a credible system design and a technology development roadmap that makes these missions feasible. Active related-technology development is occurring in ground-based testbeds, (e.g., *SIFFT*, *FTTB*, and *FIT*) and interferometric observatories (e.g., *CHARA*, *VLTi*, *COAST*, *NPOI*, and *MRO*) to ensure that both the Pathfinder and full-missions could be done on the timescales suggested. Current information on all these efforts can always be found at <http://hires.gsfc.nasa.gov/si/>.

Acknowledgments. Contributions are gratefully acknowledged from the wide range of science and technology investigators and collaborators on the *Stellar Imager* Vision Mission Team (see Carpenter et al. 2006b). This work was supported, in part, by Vision Mission Study grants from NASA HQ to NASA-GSFC and from GSFC to Smithsonian Astrophysical Observatory, Seabrook Engineering, SUNY/Stonybrook, U. Colorado/Boulder, and STScI. Substantial complementary internal institutional support is gratefully acknowledged from all of the participating institutions.

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