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The Stellar Imager (SI) Project: A Deep Space UV/Optical Interferometer (UVOI) to Observe the Universe at 0.1 Milli-arcsec Angular Resolution

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Abstract The Stellar Imager (SI) is a space-based, UV/Optical Interferometer (UVOI) designed to enable 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and of the Universe in general. It will also probe via asteroseismology flows and structures in stellar interiors. SI's science focuses on the role of magnetism in the Universe and will revolutionize our understanding of the formation of planetary systems, of the habitability and climatology of distant planets, and of many magneto-hydrodynamically controlled processes, such as accretion, in the Universe. The ultra-sharp images of SI will revolutionize our view of many dynamic astrophysical processes by transforming point sources into extended sources, and snapshots into evolving views. SI is a "Flagship and Landmark Discovery Mission" in the 2005 Heliophysics Roadmap and a potential implementation of the UVOI in the 2006 Science Program for NASA's Astronomy and Physics Division. We present here the science goals of the SI Mission, a mission architecture that could meet those goals, and the technology development needed to enable this mission. Additional information on SI can be found at: http://hires.gsfc.nasa.gov/si/.

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1 Introduction

The next major observational advances in astronomy will require quantum leaps in sensitivity (total collecting area) or in angular resolution (collector size/baselines). The former are being pursued with concepts such as the James Webb Space Telescope (JWST) and Space Ultraviolet Observatory (SUVO), which use large segmented or filled apertures. The latter will be pursued with interferometric designs such as the EASI/Solar Viewing Interferometer (SVI), Space Interferometry Mission (SIM), Terrestrial Planet Finder-I (TPF-I), Stellar Imager (SI), Life Finder (LF), Black Hole Imager (BHI), and Planet Imager (PI). SIM and TPF-I, if they fly, will primarily perform astrometry and low resolution imaging with modest baselines ($\sim$20 meters), while the true, high-resolution imagers SI, LF, BHI, and PI will require large baselines, from 0.5 to many kilometers.

SI, a "Landmark Discovery Mission" in the 2005 Heliophysics Roadmap and a candidate implementation of the UVOI (Ultraviolet/Optical Interferometer) in the 2006 Science Program for NASA's Astronomy and Physics Division, is a concept which provides this class of capability throughout the 1200 - 6600 A spectral region. It is designed to open an enormous 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 its spectral energy information, will enable the resolution of stellar surfaces and interiors (via spatially-resolved asteroseismology), 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 this resolution, 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.

2 Science Goals

The primary science goals of SI are to improve our understanding of:

- Solar and Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life
- Magnetic and Accretion Processes and their roles in the Origin & Evolution of Structure and in the Transport of Matter throughout the Universe
- Exo-solar planetary systems and debris disks

The first science goal will be addressed by observing and measuring spatial and temporal stellar surface magnetic activity patterns through ultra-high angular resolution ($\leq$ 0.1 milli-arcsec) UV imaging, and by measuring via disk-resolved asteroseismology, in broadband optical/near-UV light, 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 exoplanets 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, Darwin, PI*) will find and image planets, and by determining the impact of the activity of those stars on the habitability of the surrounding planets.

The second goal is enabled by the high angular resolution and spectral energy information provided by SI for the fine structure of a wide variety of heretofore unresolved objects and processes, including, for example:

- Active Galactic Nuclei, including the transition zone between Broad and Narrow Line Emitting Regions and the determination of the origin and orientation of their jets
- Interacting Binaries, including mass-exchange, dynamical evolution, accretion, and dynamos
- Supernovae & Planetary Nebulae: their core structure, early expansion and interaction with the Circumstellar Medium (CSM)
- Cool, Evolved Giant & Supergiant Stars and the spatiotemporal structure of extended atmospheres, pulsation, winds, shocks
- Quasars, Black-Hole Environments, etc.
- Hot Stars and their hot polar winds, non-radial pulsations, rotation, structure, and the envelopes and shells of Be-stars

The third goal will be approached in two ways: 1) exo-planets themselves will be studied by imaging transits across stellar disks and perhaps in some cases by direct imaging of the planets themselves and 2) the imaging of debris and shells surrounding infant star-disk systems and the imaging of dynamic accretion, magnetic field structure & star/disk interactions in these systems.

2.1 Fit to NASA/ESA Science Goals

This cross-Theme mission addresses major Science Questions and Research Objectives in the 2007 NASA Science Mission Directorate Science Plan (see Table 2.1, page 15) in both the Heliophysics and Astrophysics Science Areas.

In the Heliophysics arena it will address, via its population study of the magnetic activity of a broad range of stars (in comparison with the Sun) and its impact on the climate and habitability of surrounding planets, the primary goal of the Division: “Understand the Sun and its effects on Earth and the Solar System”, and, in particular, the associated science questions “How and why does the sun vary?” and “What are the impacts on humanity?”

In the Astrophysics arena, SI addresses, through its studies of magnetic structures and processes which control those structures throughout the Universe (e.g., in stars, forming extra-solar planetary systems, supernovae, Active Galactic Nuclei (AGN), etc.) the science question: “How do planets, Stars, Galaxies, and cosmic structure come into being?”, and, through its investigation of the impact of stellar magnetic activity on the climate and habitability of surrounding planets, the science questions “When and how did the elements of life and the Universe arise?” and “Is there Life elsewhere?”. It executes the Astrophysics research objective of understanding “how individual stars form and how those processes ultimately affect the formation of planetary systems” and will help, via observations of planetary transits, to “create a census of extrasolar planets” and “measure their properties”.

SI has many synergies with the ESA Luciola Cosmic Vision concept (a many-element hypertelescope for general Astrophysics, PI=Antoine Labeyrie), both in terms of science goals and in the technology development needed to enable the missions.

3 Mission Architecture

3.1 Performance Requirements

The science goals of *SI* lead to the following performance requirements:

- wavelength coverage: 1200-6600 Å, to include both hydrogen Ly-α and Hα
- access to UV emission lines from Lyα 1216 Å to Mg II 2800 Å for imaging of magnetic structures
  - Important diagnostics of most abundant elements
  - much higher contrast between magnetic structures and background
  - smaller baselines (UV saves 2-4x vs. optical, stellar active regions 5x larger in UV)
  - $\sim$ 10-Å UV pass-bands, to isolate emission from specific ions sensitive to plasmas of particular temperatures, e.g., C IV (100,000 K) & Mg II h&k (10,000 K)
- broadband, near-UV or optical coverage (3,000-10,000 K) for high temporal resolution spatially-resolved asteroseismology to resolve internal stellar structure
- angular resolution of 50 micro-arcsec at 1200 Å (120 micro-arcsec @2800 Å)
- $\sim$ 1000 pixels of resolution over the surface of nearby ($\sim$4 pc) dwarf stars and over the surface of the many giant and supergiant stars within $\sim$2 kpc.
- energy resolution/spectroscopy of detected structures of at least R=100, up to an R=20000 if possible
- a long-term ($\sim$ 5 year requirement, $\sim$ 10 year goal) mission to study significant fractions of stellar activity cycles: individual telescopes/hub(s) must be able to be refurbished or replaced
- must be able to observe the full sky over the course of 1 year

3.2 Design from Vision Mission Study

NASA commissioned a "Vision Mission Study" of SI in 2004-2005, which developed a design that meets these performance requirements and science goals. Details can be found in the final report available at http://hires.gsfc.nasa.gov/si/ and in Carpenter et al. (2006b). We summarize that design here and then discuss some alternative design options under current consideration.

The design that came out of the Vision Study 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. The Vision Mission SI design is summarized in Figure 1. The capabilities of this SI design are illustrated in Figure 2, which shows simulations of observations possible with SI.

The individual mirrors in this design are fabricated as ultra-smooth, UV-quality flats which are actuated to produce the extremely gentle curvature (f/1000 - f/10000) 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 (f/5000 curvature).

A one-meter primary mirror size is sufficient to ensure good signal/noise for surface imaging of the primary stellar activity targets. For the asteroseismic observations of a few carefully selected targets ($\sim$1 per year), we plan month-long observations in order to build up the millions of counts needed for modal analysis. 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 cm-level 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 (a second hub can be prepositioned for the next observation, while the first is in use). The observations are scheduled to minimize slew distances (typically no more than 15 degrees), given the expected 10 deg/hour slew rate for re-targeting and we budget 1 hour of overhead to settle on and acquire a new target after each slew. 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.

The science goals, mission and performance parameters of the SI Vision Mission concept are summarized in a single panel in Figure 3.

3.3 Current and Future Design Efforts

After the completion of the Vision Mission Study, we have continued to develop the mission concept, both expanding upon the science goals of the mission and considering alternative architectures for achieving the science objectives of the mission in better or more efficient ways.

We are investigating alternative beam combination techniques, such as hypertelescope designs (Labeyrie 2007) that could improve the sensitivity of the observatory and a Spatial Frequency Remapper, or SFR, (Mozurkewich, Carpenter, & Lyon 2007) that will redirect the beams from the 2D primary array mirrors into a non-redundant linear array that can be crossed-dispersed to obtain spectral information, dramatically increasing the science output of the facility.

We are also developing a "light bucket" mode, in which all the photons from all the mirrors are channelled down into a single aperture/slit, without phasing the beams for imaging synthesis, and sent into a spectrograph for analysis of very faint sources. 30 one-meter diameter mirrors used in this fashion have a collecting area of 23.6 square meters, equivalent to a single monolithic mirror with a diameter of 5.5 meter (about 5x the light gathering power of HST).

We continue to probe the best way to accomplish precision formation flying of a many-element system, considering both free-flying spacecraft using thrusters such as Field Effect Electric Propulsion (FEEP) (Mohan et al. 2007) vs. electromagnetic formation flying (EMFF), as well as tethered concepts which would require fewer, but more mobile elements. The hub would be slewed using Hall Thrusters to obtain higher thrust capability for the higher mass hub. Algorithms for deployment, rough and fine alignment of the spacecraft, and for ensuring that the beams from the primary array mirrors can be delivered through the aperture plate of the combiner have been developed.

We have also examined the possibility of using the new Ares V launch vehicle being developed for the NASA Moon/Mars Initiative. Though not needed for the current "baseline design" from the Vision Mission, it would be extremely useful for designs utilizing larger primary mirrors (2m or larger, vs. the 1m meters in the current design), if those larger mirrors are deemed desirable to support the observation of fainter, likely cosmological, targets or to enable faster asteroseismic observations of (more) stars.

4 Technology Development for SI

4.1 Technology Development Required to Enable Mission

The major technology challenges (and approximate Technology Readiness Levels) to building *SI* are:

- formation-flying of 30 spacecraft (3-4)
  - deployment and initial positioning of elements in large formations
  - real-time correction and control of formation elements
  - staged-control system (km → cm → 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 (3)
  - 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 (4)
- methodologies for ground-based validation of distributed systems (2)
- light-weight UV quality mirrors with km-long radii of curvature (using active deformation of flats) (3)
- mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test (4)

4.2 Technology Maturation Plan

The major challenges on this technology development 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, including a Spatial Frequency Remapper (Mozurkewich, Carpenter, & Lyon 2007).

The results from these testbeds and studies will be combined with experience from ground-based interferometers, such as *Center for High Resolution Astronomy (CHARA), Navy Prototype Optical Interferometer (NPOI), Cambridge Optical Aperture Synthesis Telescope (COAST), Very Large Telescope Interferometer (VLTI)* and *Magdelena Ridge Observatory Interferometer (MROI)*, to enable a small, space-based UV/Optical Interferometry 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 perhaps 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 or other Black Hole Imager (BHI)* and the *Submillimeter 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, LF, and PI.*

5 Cost of Mission

Although SI is clearly a "Large Strategic Mission" (substantially more than $600 M) in the current NASA parlance, the actual cost of the mission depends on many variables in the design and there is much room within the designs for adjusting to a target range if required. Cost control options include trading the number (and size) of primary mirror elements vs. number of times they must be reconfigured to obtain a quality image vs. the amount of time that must be spent on each target, the required lifetime of the observatory, the exact approach taken to carry-out the precision formation flying (EMFF vs. thrusters, for example), etc. Although its operation at shorter wavelengths than some other space-based interferometers (not the X-ray BHI/MAXIM though!) decreases some tolerances, it has significant advantages in other areas over the IR-submillimeter planet-finding/cosmological interferometers which require cryogenic cooling and/or nulling.

6 Status of SI

SI has been included in the NASA Heliophysics Division Roadmap since 2000. It was selected by NASA HQ in 2003 for concept development as a NASA "Vision Mission" by NASA/Goddard Space Flight Center (GSFC) in partnership with Lockheed Martin Advanced Technologies Center (LMATC), Smithsonian Astrophysical Observatory (SAO), Ball Aerospace Technologies Group (BATC), Northrop Grumman Space Technologies (NGST), Marshall Space Flight Center (MSFC), Jet Propulsion Laboratory (JPL), and the University of Colorado/Boulder (CU). Technology development for SI is proceeding on several fronts: 1) the Fizeau Interferometry Testbed (FIT) is developing nm-level closed-loop optical control of a multi-element array (GSFC), 2) the Synthetic Imaging Formation-Flying Testbed (SIFFT) is developing cm-level formation-flying of an array of spacecraft (GSFC/MSFC/Massachussets Institute of Technology (MIT)), and 3) the GSFC Integrated Mission Design Center and Instrument Synthesis and Analysis Lab studies have produced a system design and a technology development roadmap that will enable the mission.

Work continues on optimizing the SI designs and minimizing the cost of the mission, while ensuring that all its science goals are fully met. The SI Team is working to expand the technology development plans and costing efforts to ensure both are as robust as possible.

7 Acronyms

BATC - Ball Aerospace Technologies Corporation

BHI - Black Hole Imager

CHARA - Center for High Angular Resolution Astronomy

COAST - Cambridge Optical Aperture Synthesis Telescope

CU - University of Colorado at Boulder

FIT - Fizeau Interferometer Testbed

GSFC - Goddard Space Flight Center

FKSI - Fourier Kelvin Stellar Interferometer

JPL - Jet Propulsion Laboratory

LF - Life Finder

LMATC - Lockheed Martin Advanced Technologies Center

MAXIM - Micro-Arcsec X-ray Imaging Mission

MROI - Magdelena Ridge Observatory Interferometer

MSFC - Marshall Space Flight Center

NGST - Northrop Grumman Space Technologies

NPOI - Navy Prototype Optical Interferometer

PI - Planet Imager

PSF - Point Spread Function

SAO - Smithsonian Astrophysical Observatory

SI - Stellar Imager

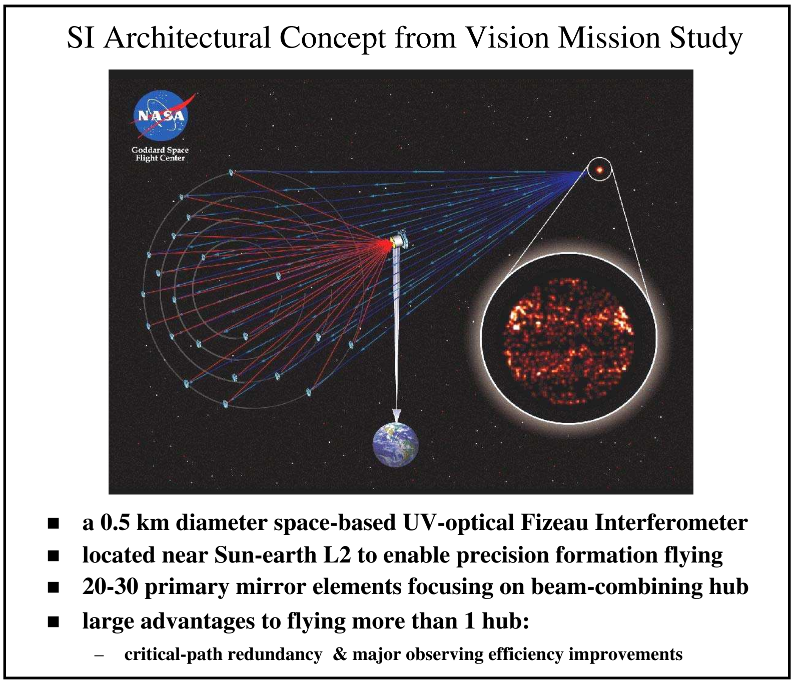
SIFFT - Synthetic Imaging Formation Flying Testbed

SPECS - Submillimeter Probe of the Evolution of Cosmic Structure

SPIRIT - Space Infrared Interferometric Telescope

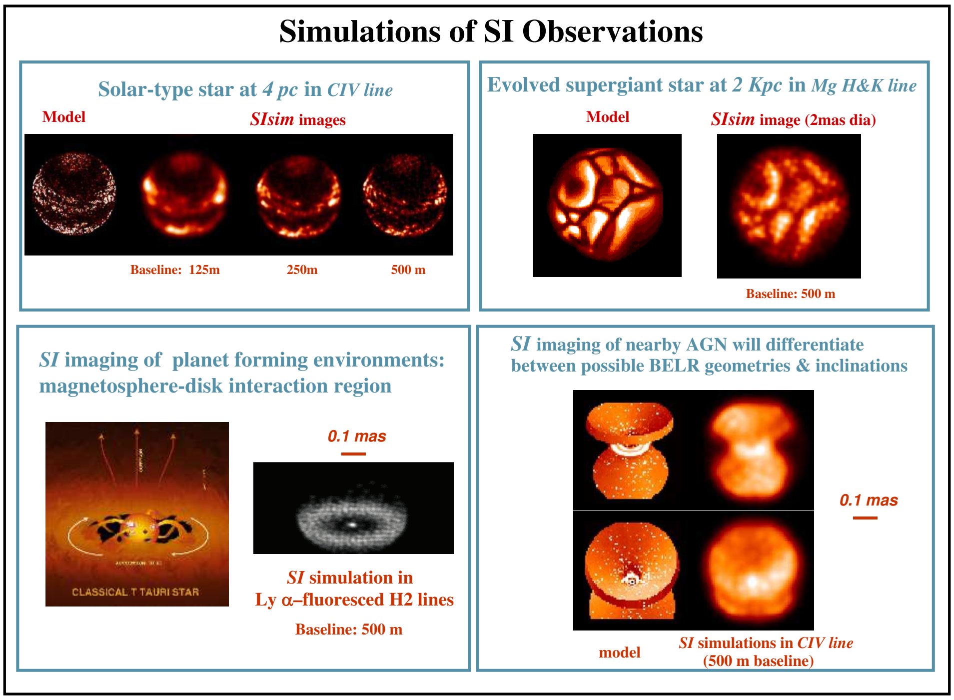
SPHERES - Synchronized Position Hold Engage Reorient Experimental Satellites

VLTI - Very Large Telescope Inteferometer


SI Architectural Concept from Vision Mission Study

- **a 0.5 km diameter space-based UV-optical Fizeau Interferometer**
- **located near Sun-earth L2 to enable precision formation flying**
- **20-30 primary mirror elements focusing on beam-combining hub**
- **large advantages to flying more than 1 hub:**
  - **critical-path redundancy & major observing efficiency improvements**

Fig. 1.— A summary of the current baseline *SI* architecture, with an artist's illustration on top and the basic characteristics of the observatory listed below.


Simulations of SI Observations

Solar-type star at *4 pc* in *CIV line*

Model **SI*sim* images**

Baseline: 125m **250m** **500 m**

Evolved supergiant star at *2 Kpc* in *Mg H&K line*

Model **SI*sim* image (2mas dia)**

Baseline: 500 m

***SI* imaging of planet forming environments: magnetosphere-disk interaction region**

0.1 mas

***SI* simulation in Ly α–fluoresced H2 lines**

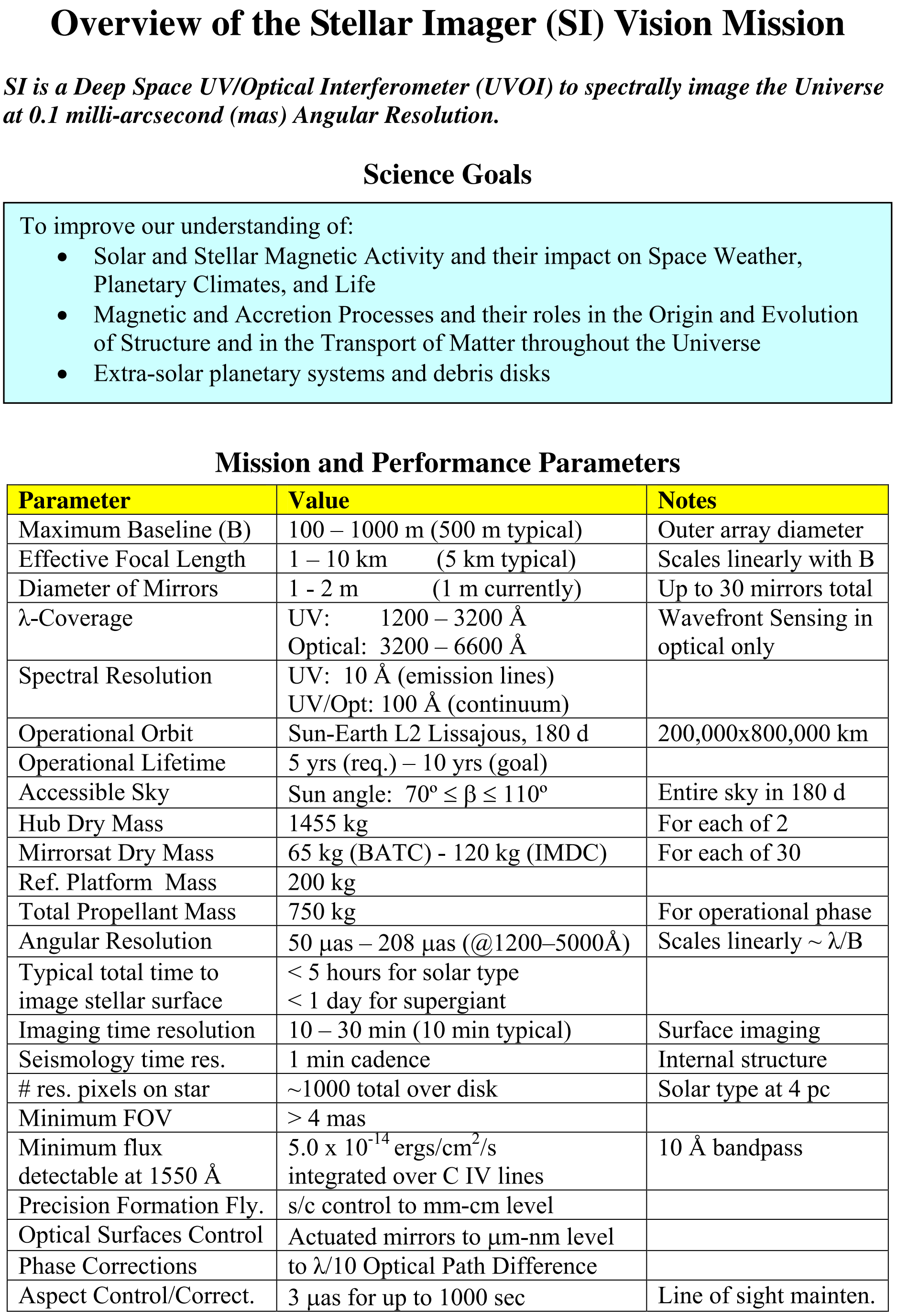
Baseline: 500 m

***SI* imaging of nearby AGN will differentiate between possible BELR geometries & inclinations**

0.1 mas

model ***SI* simulations in *CIV line* (500 m baseline)**

Fig. 2.— Simulations of SI's observational capabilities on various astronomical targets, using SISIM software created by Rajagopal et al. (2003)



Overview of the Stellar Imager (SI) Vision Mission

SI is a Deep Space UV/Optical Interferometer (UVOI) to spectrally image the Universe at 0.1 milli-arcsecond (mas) Angular Resolution.

Science Goals

To improve our understanding of:

- Solar and Stellar Magnetic Activity and their impact on Space Weather, Planetary Climates, and Life
- Magnetic and Accretion Processes and their roles in the Origin and Evolution of Structure and in the Transport of Matter throughout the Universe
- Extra-solar planetary systems and debris disks

Mission and Performance Parameters

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) - 120 kg (IMDC)	For each of 30
Ref. Platform Mass	200 kg	
Total Propellant Mass	750 kg	For operational phase
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	
Minimum flux detectable at 1550 Å	5.0×10^{-14} ergs/cm^2/s integrated over C IV lines	10 Å bandpass
Precision Formation Fly.	s/c control to mm-cm level	
Optical Surfaces Control	Actuated mirrors to μm-nm level	
Phase Corrections	to λ/10 Optical Path Difference	
Aspect Control/Correct.	3 μas for up to 1000 sec	Line of sight mainten.

Fig. 3.— A one-page summary of the Stellar Imager Concept, as derived during the Vision Mission Study.

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