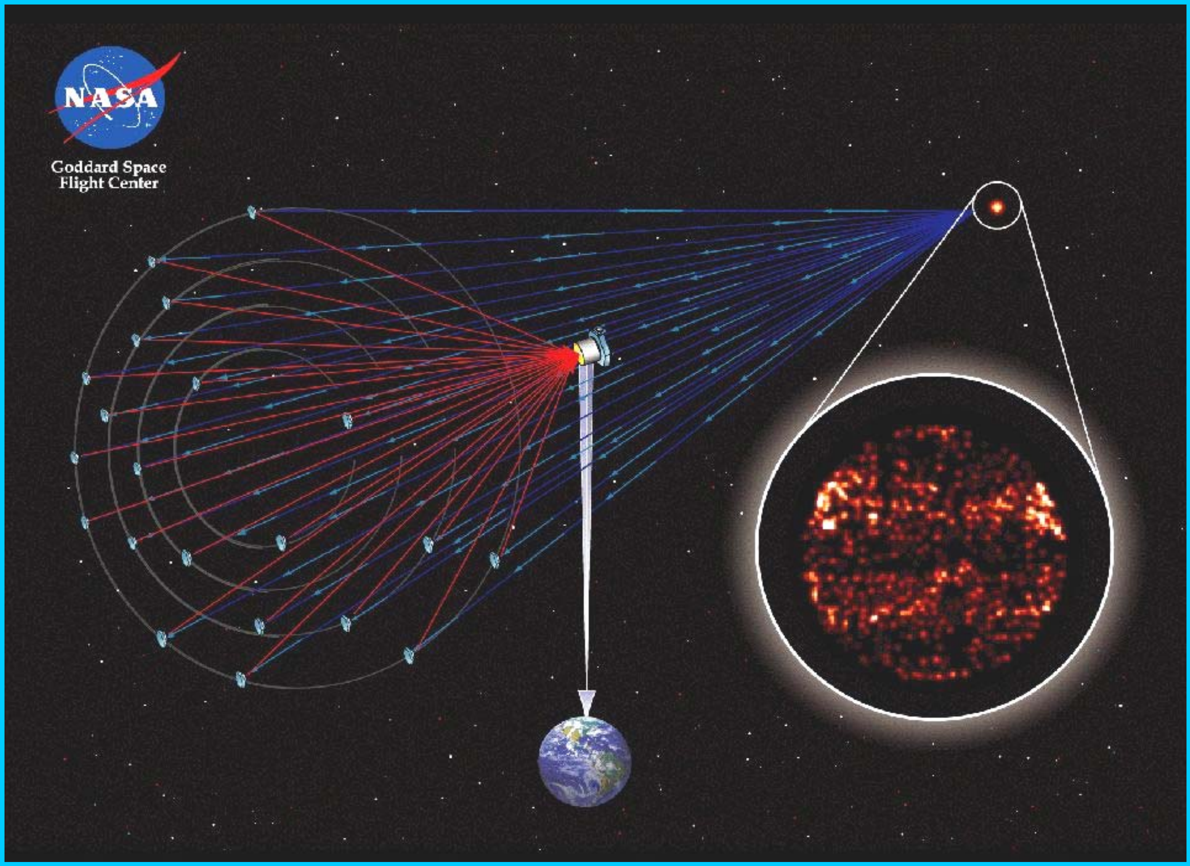
Vision Mission Study Report (15 September 2005)

SI – The Stellar Imager

A UV/Optical deep-space telescope to image stars and observe the Universe with 0.1 milli-arcsec angular resolution



Its mission:

To enable an understanding of solar/stellar magnetic activity and its impact on the:

- origin and continued existence of life in the Universe
- structure and evolution of stars
- habitability of planets

and to study magnetic processes and their roles in the origin and evolution of structure and the transport of matter throughout the Universe.

http://hires.gsfc.nasa.gov/~si/

Front Cover Illustration

The illustration on the front cover shows an artist's concept of the baseline SI design, a Fizeau Interferometer with 20-30 one-meter primary mirrors, which are 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 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 from 1 – 10 km distant. The focal length scales linearly with the diameter of the primary array: a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array with a focal length of 10 km.

This Stellar Imager Vision Mission Report presents the results of a study carried out by a broad collaboration led by the Goddard Space Flight Center as shown on the next page. The principal authors of this Report and their primary areas of expertise include:

Kenneth G. Carpenter (GSFC) – Principal Investigator and Lead Author
Carolus J. Schrijver (LMATC) – Solar/Stellar Magnetic Activity Science Lead
Margarita Karovska (SAO) – "Universe" Science Lead
Ron Allen (STScI) – Phase Closure, Interferometer Design/Performance/Simulator
Jim Breckinridge (JPL) – Alternative Architectures
Alex Brown (CU/Boulder) – Target Selection
Peter Chen (CUA) – Lightweight Mirrors
David Folta (GSFC) – Deployment and Orbit and Formation Maintenance
Graham Harper (CU/Boulder) – Effects of ISM/Extragalactic Background
Kate Hartman & Joe Dolan (GSFC) – Editorial Assistance
Steve Kilston & Rich Reinert (BATC) – Operations Assurance/Validation, Mirrorsat design
Barry Kirkham (NGST) - Operations
Jesse Leitner (GSFC) – Precision Formation Flying
Alice Liu (GSFC) – Staged-Control Systems
Richard Lyon (GSFC) – Optical Modeling, Wavefront Sensing & Control, Image Reconstruction
Rud Moe (GSFC) – Role of Humans/Robots
David Mozurkewich (Seabrook Eng.) – Interferometer Architectures/Beam Combiner Designs
Charley Noecker (BATC) – Interferometer Architectures/Beam Combiner Designs
Sten Odenwald (QSS) & Carol Grady (CUA) – Education/Public Outreach
James Phillips (SAO) – Precision Metrology
Eric Stoneking (GSFC) – Staged-Control Systems, Target Acquisition
Fred Walter (SUNY/Stonybrook) – Design Reference Mission

Additional contributions are gratefully acknowledged from the wide range of science and technology investigators and collaborators on the Stellar Imager Vision Mission Team, as shown on the next page.

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.

Stellar Imager Vision Mission Team

The Stellar Imager Vision Mission concept is under development by NASA's Goddard Space Flight Center (K. Carpenter, PI), 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:

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

Ball Aerospace & Technologies Corp.	Lockheed Martin Adv. Tech. Center
NASA's Jet Propulsion Laboratory	Naval Research Laboratory/NPOI
Northrop-Grumman Space Tech.	Seabrook Engineering
Sigma Space Corporation	Smithsonian Astrophysical Observatory
Space Telescope Science Institute	State Univ. of New York/Stonybrook
Stanford University	University of Colorado at Boulder
University of Maryland	University of Texas/Arlington
European Space Agency	Kiepenheuer Institute
Potsdam Astronomical Institute	University of Aarhus

- **Institutional and topical leads from these institutions include:**
  K. Carpenter, C. Schrijver, R. Allen, A. Brown, D. Chenette, D. Mozurkewich, K. Hartman, M. Karovska, S. Kilston, J. Leitner, A. Liu, R. Lyon, J. Marzouk R. Moe, N. Murphy, J. Phillips, F. Walter

- **Additional science and technical collaborators include:**
  T. Armstrong, T. Ayres, S. Baliunas, C. Bowers, G. Blackwood, J. Breckinridge, F. Bruhweiler, S. Cranmer, M. Cuntz, W. Danchi, A. Dupree, M. Elvis, N. Evans, C. Grady, F. Hadaegh, G. Harper, L. Hartman, R. Kimble, S. Korzennik, P. Liewer, R. Linfield, M. Lieber, J. Leitch, J. Linsky, M. Marengo, L. Mazzuca, J. Morse, L. Mundy, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, D. Sasselov, S. Saar, J. Schou, P. Scherrer, M. Shao, W. Soon, G. Sonneborn, R. Stencel, B. Woodgate

- **International Collaborators include:**
  J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe

- **Student Participants include:**
  Linda Watson (undergrad-Univ. Florida/CfA), Darin Ragozzine (undergrad-Harvard, grad-CalTech), Mikhail Dhruv (high school), Fonda Day (undergrad/CU)

Quick Facts: The Stellar Imager (SI) Vision Mission

SI is a UV-Optical, Space-Based Interferometer for 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and stellar interiors, via asteroseismology, and of the Universe in general.

Science Goals

To understand:
- Solar and Stellar Magnetic Activity
  and their impact on Space Weather, Planetary Climates, and Life
- Magnetic Processes and their roles in the Origin and Evolution of Structure
  and in the Transport of Matter throughout the Universe

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 – 5000 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: $70^{o} \leq \beta \leq 110^{o}$	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.

Executive Summary

The ultra-sharp images of the Stellar Imager (SI) will revolutionize our view of many dynamic astrophysical processes: The 0.1 milliarcsec resolution of this deep-space telescope will transform 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 in support of the Living With a Star program in the Exploration Era. 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.

Primary Science Goals for the Stellar Imager

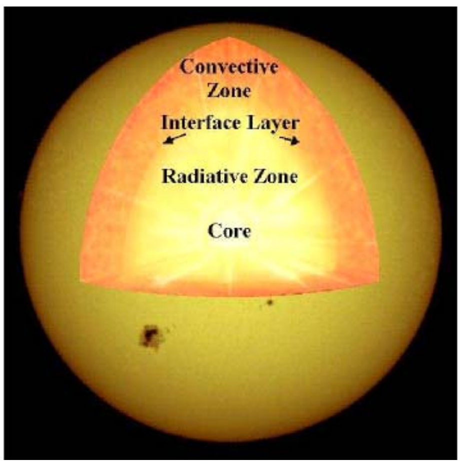


Figure ES-1: Internal structure of the Sun: an essentially static shell surrounds the nuclear furnace in the core, enveloped by a layer in which convective motions transport the solar luminosity. In doing so, these motions drive the solar dynamo.

Most of us rarely give the Sun a second thought. We do not question its presence or its apparent stability as we see it traverse the sky every day. The Sun is, however, a variable star. Its variability affects society by modulating Earth's climate. It also affects our technology, upon which we are becoming ever more reliant: eruptions on the Sun disrupt communications; affect navigation systems; cause radiation harmful to astronauts exploring beyond the Earth's atmosphere and to airline passengers traveling through it; and occasionally push power grids to fail. The cause of this variability is the Sun's magnetic field. This intangible and unfamiliar fundamental force of nature is created in the convective envelope of the Sun (see Fig. ES-1, showing the Sun's internal structure) by a process that we call the dynamo. The Stellar Imager will help us understand the dynamo process in the Sun by observing magnetic processes in Sun-like stars and in other astrophysical systems. That insight into solar activity will help us mitigate the effects of space weather, both on Earth and beyond.

Historical records show that the Sun can change its activity significantly; both upward and downward (see Fig. ES-2). Activity decreased, for example, for multiple decades during the 17th Century when Earth experienced the Little Ice Age. A sustained increase in activity – such as happened during the medieval Grand Maximum – may cause a warm spell, and will be associated with an increase in the frequency of space storms, and in the ultraviolet radiation that is harmful to life on Earth.

The dynamo is one of the truly large mysteries in astrophysics. There is at present no model for a stellar dynamo that can be used to forecast the Sun's activity on the time scale of months to decades. We know that the solar dynamo operates throughout the outermost 200,000 km of the solar interior, in and just below the convective envelope. The vastness of this volume relative to the smallest relevant scales precludes a complete numerical model. There is not even a generally accepted approximate dynamo model. In fact, the experts do not agree where most of the dynamo action occurs within the stellar interior, or which are the key processes that are involved.

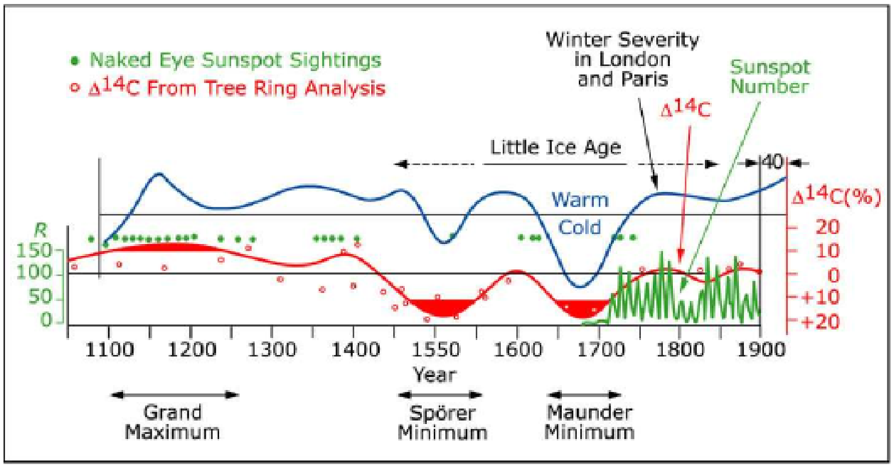


Figure ES-2: Solar activity and Earth's climate:

the nature of the link is yet to be understood, but the correlation suggests that solar activity somehow couples into the Earth's climate system. (From the Living With A Star initiative)

What makes understanding the solar dynamo so difficult? That answer involves two of the major developments of science in the 20th century: a stellar dynamo involves both *non-linear* and *non-local* effects. Such a dynamo can exhibit fundamentally different properties even for relatively small changes in the processes involved. In other words: if a dynamo model does not incorporate all relevant physics in sufficient detail, it will not enable us to predict solar activity on time scales of years or more, or to understand its gross characteristics in the distant past and future. In order to develop a dynamo model with predictive value, we must establish which processes are involved, and which approximations are allowed.

It would take hundreds of years to validate a dynamo model for the Sun using only observations of the Sun, given its irregular 11-year magnetic heartbeat and the significant overlying long-term modulations. The more efficient alternative is to test and validate dynamo models using Stellar Imager observations of the variable magnetic activity of a broad sample of stars. Indeed, surface magnetic activity records of stars on or near the lower main sequence (e.g. from the Mount Wilson Observatory Ca II H&K survey, Soon & Yaskell 2004) show variability similar to the Solar variability, including Maunder minimum-like phases, on time scales of many decades. For example, Figure ES-3 shows two stars with cycles like that of the Sun, with one (the K0 V star HD 3651) showing a rapid decline in its chromospheric activity, possibly reflecting entry into a Maunder-minimum state.

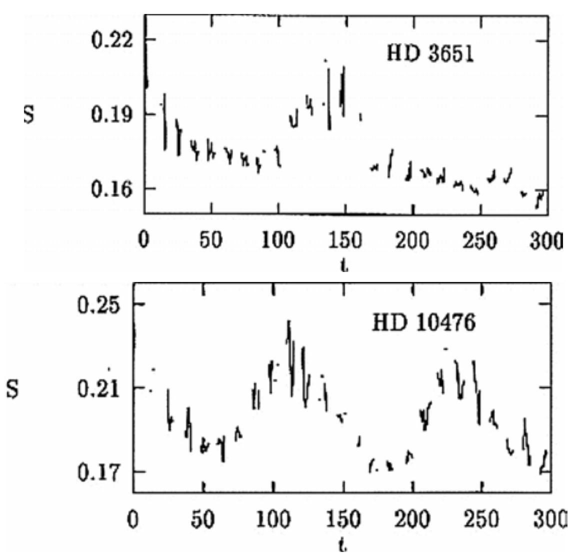


Figure ES-3: Going into a Maunder minimum?

The chromospheric activity of HD 3651 (top panel), as measured by CaII emission strength, is fading over the years, suggesting that this star is rapidly going into a Maunder-minimum state, while HD 10476 (lower panel) continues to cycle like the current Sun. The time "t" on the horizontal axis is measured in months. (Frick et al. 1997).

Key to successfully navigating the route to a workable, predictive dynamo model is the realization that *in order to understand the solar dynamo, we need a population study: we need to study the dynamo-driven activity 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 and our prediction ability lies in spatially-resolved imaging of the dynamo-driven activity patterns on a variety of stars. These patterns, and how they depend on stellar properties (including convection, differential rotation and 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 nonlinear 3-dimensional dynamo theory, and to validate the ultimate model.

Direct, interferometric imaging – the goal of the Stellar Imager - is the only way to obtain adequate information on the dynamo patterns for stars of Sun-like activity. Alternative methods that may offer limited information on spatial patterns on much more active stars fail for a Sun-like star:

> "What then is a magnetic field and how does it operate in the astronomical universe to cause all the 'trouble' that we have attributed to it? What is this fascinating entity that like a biological form is able to reproduce itself and carry on an active life in the general outflow of starlight and from there alter the behavior of stars and Galaxies?" E.. Parker, 1979

- rotationally-induced Doppler shifts in such stars are too small compared to the line width to allow Zeeman-Doppler imaging (see section 1.3.2.1)

- the activity level is insufficient to lead to significant spectral changes associated with magnetic line splitting

- rotational modulation measurements are inherently subject to deconvolution limitations that leave substantial ambiguities in the latitude distributions, locations and sizes of spots, and cannot be used to understand the facular contributions in quiet regions that are governed by field dispersal and differential rotation.

The direct imaging by SI of stellar activity will sidestep these problems. Equally importantly, the asteroseismic observations planned with SI will determine the internal properties of stellar structure and rotation, thus directly providing crucial information relevant to the physical operation of the dynamo mechanism.

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, to its ultimate death beyond the red-giant phase during which the Sun will swell to about the size of the Earth's orbit.

Table ES-1 summarizes the observational requirements that must be met to achieve SI's prime science goals, which are discussed in more detail in Chapter 1.

Table ES-1: Requirements to achieve the prime science goals of the Stellar Imager

Imaging stellar activity using emission from the outer atmosphere:
Image nearby main-sequence and giant stars with at least 1,000 resolution elements on their surface, in UV emission lines originating in the outer atmosphere; *requires a baseline of 500 m for a star at 4 parsec*.
Construct images within ~1% of the stellar rotation period, i.e. 6 h for a star like the Sun; *requires efficient reconfiguration and/or a large number of interferometer components, and an increasing number of interferometer components for increasing rotation rate.*
Compile at least ~ 30 images within one stellar rotation; requires optimized target lists and efficient repointing.
Revisit stars during 3-6 month intervals, spanning > 5 yrs; requires a long operational life, and preferably replaceable component spacecraft.
Imaging stellar interiors with asteroseismic techniques:
Achieve 30 resolution elements on stellar disks with 1 min. cadence, in a broad passband in the optical; *requires at least 9 optical elements, with meter-class collecting areas.*
Continuous observations for ~one rotation, with a duty cycle better than ~ 90%; requires stable environment.

General Astrophysics with the Stellar Imager

Of all the stars in the Universe, only one has been seen as it truly is...highly complex and ever changing. Yet, the Sun is only one of many types of stars. Our comprehension of stars forms the foundation of our understanding of the Universe. Magnetic fields affect the evolution of stars and planetary systems in all phases, from the formation of the star and its planets, to the habitability of these planets through the billions of years during which they live with their stars. *SI will enable detailed study of magnetic processes and their roles in the Origin and Evolution of Structure and in the Transport of Matter throughout the Universe*.

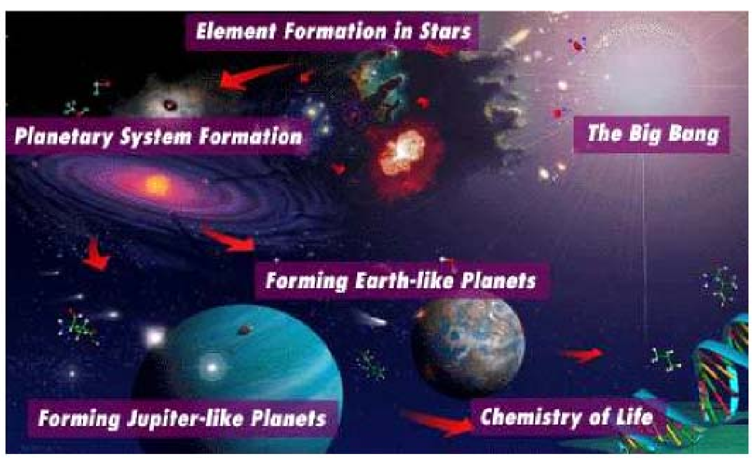


Figure ES-4: The history of the Universe, from the Big Bang, through the formation of stars and planets, to life.

The Stellar Imager focuses on stellar magnetic activity and its role in planetary system formation, the origins of life, space weather, and the habitability of Earth. (Image by P. Rawlings, JPL)

A long-baseline interferometer in space will benefit many fields of astrophysics. Imagine, for example, unprecedented images of active galactic nuclei, quasi-stellar objects, supernovae, interacting binary stars, supergiant stars, hot main-sequence stars, star-forming regions, and protoplanetary disks. Figure ES-5 shows simulated SI results, computed using SISIM (Rajagopal et al. 2003), assuming 30 mirror elements distributed in a non-redundant pattern with the indicated maximum baselines.

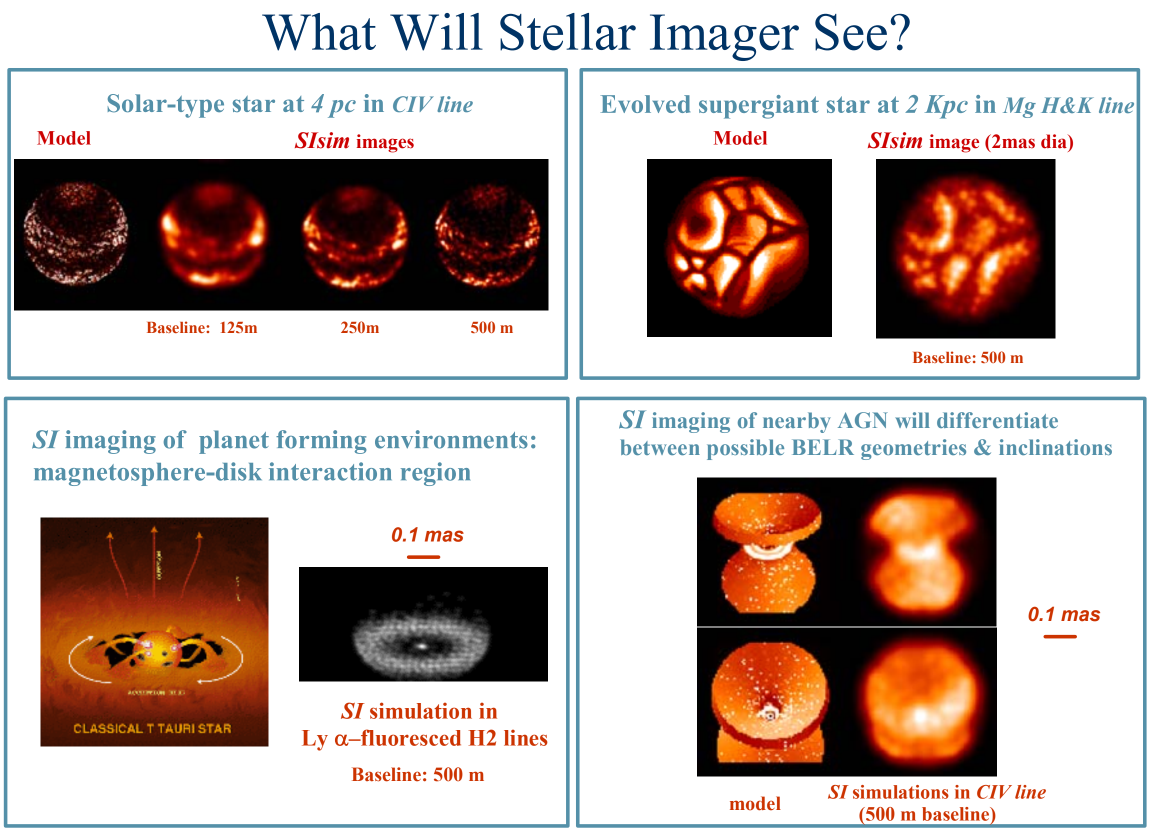


Figure ES-5: Simulations of some of SI's capabilities for UV imaging.

SI will produce images with hundreds of times more detail than Hubble, which in turn will bring the study of dynamical evolution of many astrophysical objects into reach: hours to weeks between successive images will detect dramatic changes in many objects, e.g., mass transfer in binaries, pulsation-driven surface brightness variation and convective cell structure in giants and supergiants, jet formation and propagation in young planetary systems, reverberating active galactic nuclei, and many others (see Fig. ES-6).

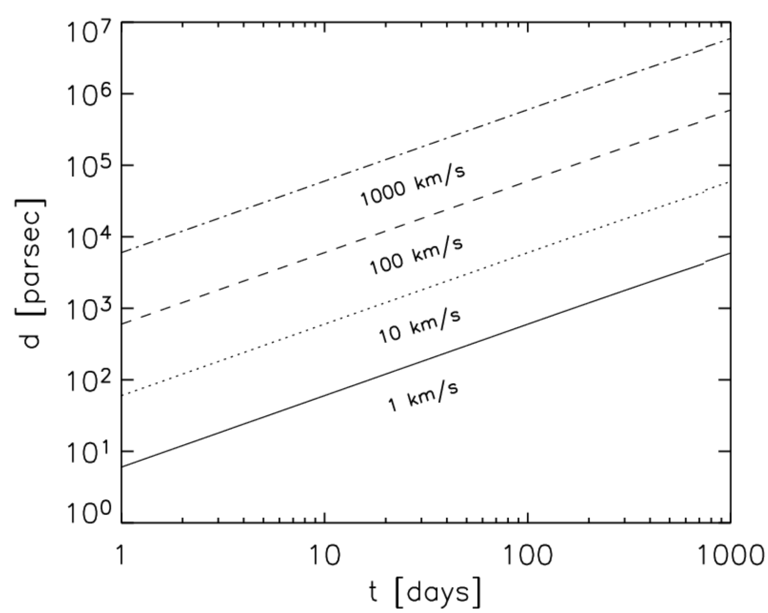


Figure ES-6: Minimum time interval between successive SI images required to resolve the motion of a feature moving at different speeds (line labels) as a function of the object's distance.

The SI Mission Concept

The Stellar Imager (SI) is a mission to understand the various effects of magnetic fields of stars, the dynamos that generate them, and the internal structure and dynamics of the stars in which these dynamos operate. *The ultimate goal of the mission is to achieve the best -possible forecasting of solar activity as a driver of climate and space weather on times scales ranging from months up to decades, and an understanding of the impact of stellar magnetic activity on life in the Universe. The road to that goal will revolutionize our understanding of stars and stellar systems, the building blocks of the Universe.*

The Stellar Imager is a UV/optical interferometer designed to provide images with some 1,000 picture elements of a sample of dozens of stars over a period of up to a decade. This will reveal the surface patterns of dynamos (e.g., Fig. ES-7) in widely different stars, allowing us to differentiate between the various dynamo models.

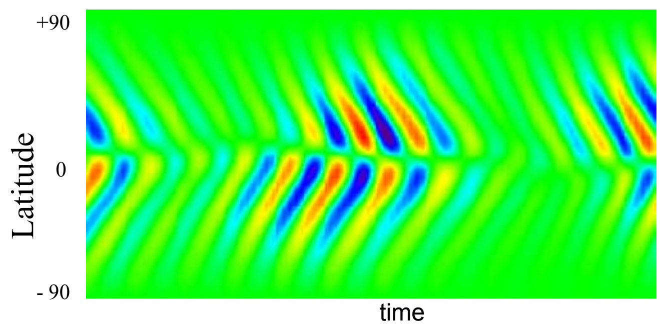


Figure ES-7: The evolution of a latitude-dependent activity pattern for a model dynamo.

Observing the shape of such a pattern and of the large-scale surface flows that help shape it for at least one cycle for a sample of stars will help us discriminate between dynamo models. (Figure from S. Tobias)

SI, with a characteristic angular resolution of 0.1 milli-arcseconds at 2000 Å, represents an advance in image detail of several hundred times over that provided by the Hubble Space Telescope. The Stellar Imager will zoom in on what today - with few exceptions - we only know as point sources, revealing processes never before seen, thus providing a tool as fundamental to astrophysics as the microscope is to the study of life on Earth. The potential of SI for imaging solar-type activity in a star at 4pc is illustrated in Fig. ES-8.

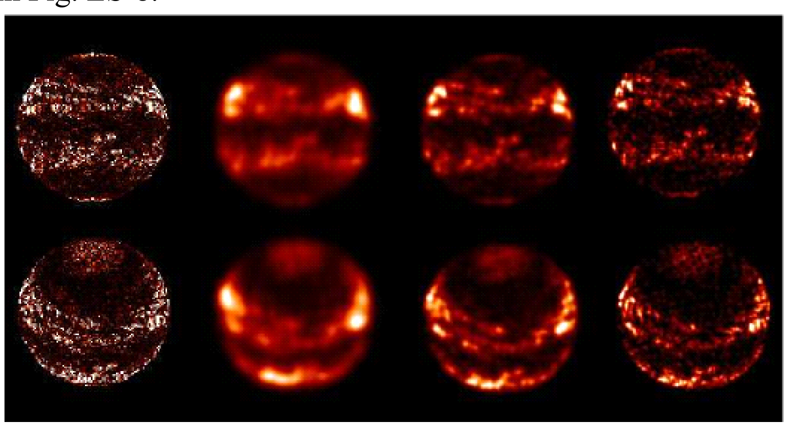


Figure ES-8: The potential of the Stellar Imager:

Model CIV 1550 Å images of a star like the Sun (left) and simulated images for maximum baselines of 125 m, 250 m, and 500 m (2nd-4th columns). The simulated reconstructions assume observations of a star at 4 pc with 870 baseline pairs (e.g. 2 configurations of a 30-element array in a minimum ambiguity, low-redundancy layout or 20 configurations (rotations) of an array of 10 elements in a Y-formation), with 800 CLEAN iterations. The top and bottom rows show views of a Sun-like star with a rotation axis in the plane of the sky and with that axis tilted by 40°, respectively. (Simulations computed with SISIM/Rajagopal et al. 2003)

The full-scale SI is an ultraviolet/optical aperture synthesis imager composed of at least 9, up to perhaps as many as 30, array elements on what we call mirrorsats and a central hub with focal-plane instrumentation that allows spectral energy resolution in pass bands from a few up to hundreds of Angstroms, throughout the UV/optical region from 1216-5000 Å.

The SI mission will allow us not only to image the surfaces of stars, but also to sound their interiors using asteroseismology in order to image internal structure, differential rotation, and large-scale circulations; this will provide accurate knowledge of stellar structure and evolution and complex transport processes, and will impact numerous branches of (astro)physics. *For arrays of 9 or more optical elements, asteroseismic imaging of structure and rotation is possible with a depth resolution of 20,000 km for a star like the Sun.*

The full SI mission may be built up by starting with a small number of optical (array) elements, perhaps utilizing both interferometry and high-resolution spectroscopy. Added optical elements will increase image quality and time resolution. Table ES-2 summarizes the primary science goals and instrument requirements.

Table ES-2: *Overview of the SI science, design, and instrument requirements*

Science requirement	**Design requirement**	**Instrument requirement**
Allow imaging in UV and optical of astrophysically interesting targets with 0.1 mas (milli-arcsec) resolution.	Optical system to be optimized for observing from 1200 Å to at least 5000 Å, in multiple UV pass bands of 2-10 Å width.	Variable effective aperture or interferometer baselines from 100 - 1000 m.
Enable imaging of stars and extended complex sources such as star- and planet-forming regions, accretion disks and jet-forming regions, interacting binaries, super massive black hole environments, etc.	Image frequency components to be high enough for complex sources, and point spread function with well-defined core regions.	20-30 apertures in non-redundant pattern to provide sufficient Fourier (u,v) coverage for ultimate image reconstruction
Image the chromospheric or transition-region emission of a star like the Sun with sufficient resolution to locate large active regions and to map the large-scale surface field.	UV/optical imaging to yield ~700 resolution elements on the disk, or 30 across its equator, for a Sun-like star at 4 pc, equivalent to a resolution of ~0.1 milli-arcseconds.	Effective aperture or interferometer baselines of at least 500 m.
Time to complete one full image should be short enough that rotational smearing does not compromise the required resolution of stellar images.	Image integration time to be less than $P/30\pi$ for a stellar rotation period P (e.g., 6 h for a Sun-like star, or 2.5 h for a star with $P = 10$ d.)	Individual primary mirrors at least 1 m in diameter; # of interferometer elements ~30, unless fast reconfiguration
Observe at least 25 magnetically-active (cool) single and binary stars over five years, each at least twice per year, to study field pattern evolution and properties of cycles.	Baseline mission to exceed 5 yr; baseline target list to include at least 25 core program stars.	Slew speeds > 10 deg/hour and accessible band on the sky (solar beta angle from 70 to 110 degrees)
Observe at least 25 cool single and binary stars with 30 images within a rotation period, each at least once per year, to measure the field source properties, differential rotation, and other large-scale flows.	Re-targeting must be completed within 2-3 h to enable observing of at least 3 Sun-like targets within a 24 h period. SI pointing to allow imaging of stars for at least 30 days continuously.	Design to allow imaging at least in a 20-30°range centered 90°from the Sun-SI direction
Enable astero-seismology in near-UV or optical to measure internal differential rotation and effects of magnetic fields on internal stellar structure.	Asteroseismological resolution of 30 elements on stellar disks, at a cadence of 1 min. for at least a stellar rotation, at a duty cycle of better than ~90%, in up to three visible passbands of up to 100 Å wide.	Effective aperture to collect 10^{12} photons/band per star per rotation period. Instantaneous number of independent baselines to exceed ~60, and thus # of optical elements to exceed ~8.

The Baseline SI Mission Design

The current baseline architecture concept (see front cover) for the full Stellar Imager (SI) mission is 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 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: a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array with a focal length of 10 km. The hub and all of the mirrorsats are free-flyers in a tightly-controlled formation in a Lissajous orbit around the Sun-Earth L2 point. 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 details of the baseline design are presented in Chapter 2. See also the "Quick Facts" sheet on page iv for additional information and specifications.

Figure ES-9 shows two launch options for SI: a single launch suffices if only one hub is deployed initially (along with a reference spacecraft and 30 mirrorsats), while two launches are needed for designs that include a second beam-combining hub.

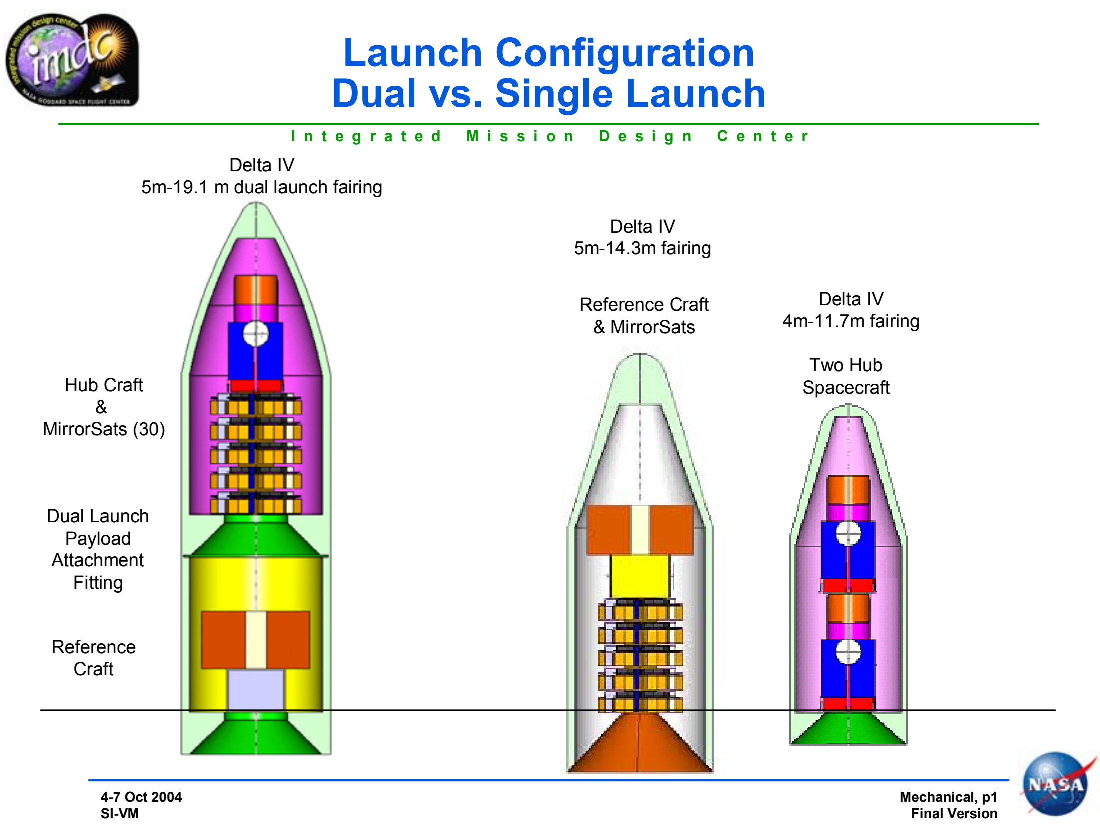


Figure ES-9: Two launch options for SI: a single Delta IV heavy vs. two Delta IV launches.

Figure ES-10 provides an overview of the selected architecture: the upper panel shows a cross-sectional schematic of the entire observatory, while the lower panel shows a close-up of the hub and its major components.

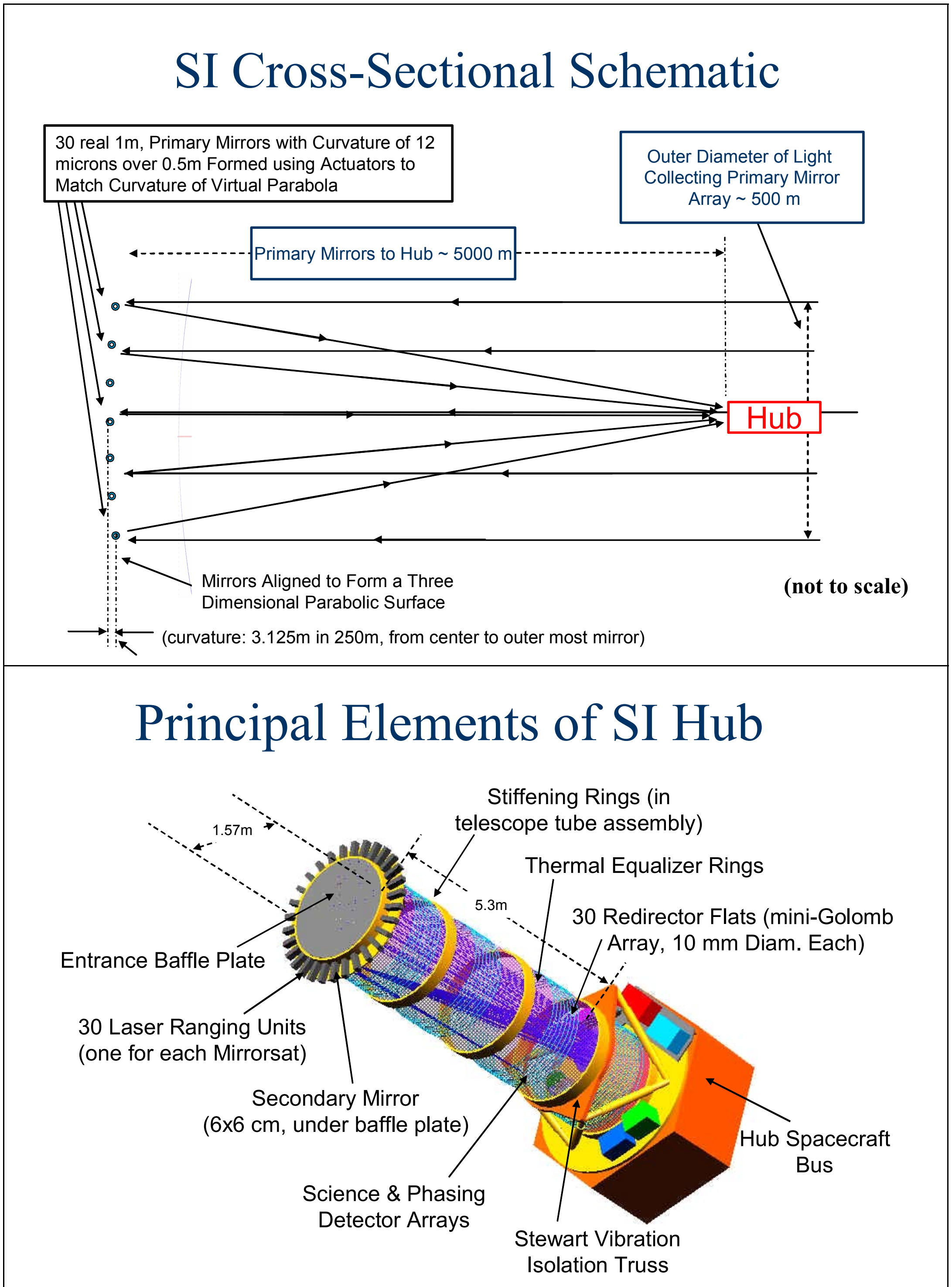


Figure ES-10: An overview of the Baseline SI Design derived during the Vision Mission Study.

Technology Developments Needed to Enable SI

The major enabling technologies needed for 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 → 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***
  - *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***
- ***methodologies for ground-based validation of distributed systems***
- ***additional challenges***
  - *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 (likely through active deformation of flats)*
  - *larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)*

Precision metrology, precision formation-flying, and the methodologies for pre-launch, ground-based testing and integration of such a large, distributed system are identified as the tallest poles among numerous technical challenges. The long mission lifetime requirement is also a concern among the designers: the hub will have redundant components, but it may be necessary to seriously consider building a backup hub for launch on-need or original deployment nonetheless, and additional backup mirrorsats will likely need to be flown so they can be put into the operating array as the original set suffers expected failures (the mirrorsats were designed as inexpensive, low-redundancy, mass-produced craft in these studies). Other technical developments of major importance and/or difficulty include the development of aspect control to 10's of μarcsecs, wavefront sensing and control of large, sparse aperture systems, larger format energy resolving detectors with higher energy resolution, and lightweight, UV-quality mirrors. Further details are given in Chapter 3.

The Stellar Imager, Science Mission Directorate Goals, and Other Projects

Fitting naturally within the NASA long-term time line, SI complements defined and proposed missions (Terrestrial Planet Finder – I, Life Finder, and Planet Imager), and with them will show us entire other solar systems, from the central star to their orbiting planets. It moreover fits on the technology roadmap that leads from interferometers like Keck and SIM to TPF-I/Darwin, MAXIM/Black Hole Imager, Life Finder, and the Planet Imager.

Stellar Imager was included in the 2000 and 2003 SEC Roadmaps and is now identified as a "*Flagship and Landmark-Discovery Mission*" in the draft 2005 Sun Solar System Connection (SSSC) Roadmap. SI is also a candidate for a "*Pathways to Life Observatory*" in the Exploration of the Universe Division (EUD) Roadmap (May, 2005). SI will provide an angular resolution over 200x that of the Hubble Space Telescope (HST), which currently offers the best angular resolution imaging in the UV, and will resolve for the first time the surfaces of Sun-like stars and the details of many astrophysical objects and processes.

The Stellar Imager is a natural culmination of science addressed with ongoing ground-based observatories and a series of space missions (Table ES-3). These efforts will provide information on long-term disk-integrated variability, large-scale internal structure and evolutionary status, distances and other fundamental stellar properties, binary properties, and low-resolution surface imaging for a subset of target classes. Other missions, such as SIM and TPF-I are space-based interferometers in the technology roadmap for the Stellar Imager.

Table ES-3*: The Stellar Imager is part of an array of space and ground-based instrumentation that contribute to our understanding of stellar activity and internal structure.*

Some of these, and their potential role in the study of stellar activity, are summarized below:

Project	Role in activity studies	Observational Technique and/or Technology
Stellar Imager	Dynamo patterns, (internal) dif. rotation binary interaction	UV/Optical interferometry <0.1 mas (milli-arcsecs)
MAXIM	Coronal structure	X-ray interferometry
Terrestrial Planet Finder	Binary properties	SI Technology precursor, IR, free -flying, nulling interferometer, 0.75 mas
Space Interferometry Mission	Binary properties	SI Technology precursor, boom interferometer
James Webb Space Telescope	Stellar mass loss, giant chromospheres	IR imaging, 100 mas
Ground-based interferometry: Keck, Large Binocular Telescope, Very Large Telescope Interferometer	Giant-star imaging, binary properties	Technology precursors
GAIA	Determination of stellar properties	High -precision parallaxes
MOST, COROT, KEPLER	Internal stellar structure	Asteroseismology
Ground-based spectroscopy	Activity monitoring, limited imaging	Automatic telescopes,(Zeeman) Doppler imaging

SI complements and builds on observations made by ground-based interferometers, by asteroseismology missions, JWST, and other missions. It complements TPF-C/I by providing a view of the space-weather environment of the planetary systems studied in those missions, and thus provides critical data needed to understand fully which of the detected planets are indeed habitable.

Table ES-4 summarizes SI's fit into the national science and technology development priorities.

Table ES-4: The Stellar Imager fits in the national science priorities, the NASA strategic plan, the Living With A Star initiative, and the technology roadmap.

SI meets scientific priorities identified by the National Academy of Sciences Astronomy and Astrophysics Survey Committee (2001). With SI we can "survey the universe and its constituents," "use the universe as a unique laboratory," "study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets," and, by focusing on the driver of space weather in past, present, and future, "understand how the astronomical environment affects Earth."
SI is responsive to a key national priority: imaging of magnetically active stars provides the only means to test any theory of solar magnetic activity as the driver of space weather and climate that can be achieved within a decade after launch.
SI fits in the NASA/OSS strategic plan: it complements the Living With A Star initiative, and shares much of the scientific and technological road that leads to other interferometers such as the Terrestrial Planet Finder, Planet Imager, and the MicroArcsecond X-ray Imaging Mission.

A Timeline for Stellar Imager

A rough flow for the development process for the SI mission or an equivalent long-baseline, UV/Optical, space-based interferometer is outlined below:

- 2005: Complete Vision Mission Study
- 2005-08: Continue studies of multi-element fine optical control with Fizeau Interferometer Testbed (FIT)
- 2005->: Continue other technology development efforts, including precision formation flying, micro-newton level thrusters, wavefront sensing and control, methodologies for integration and test of large distributed system, energy resolving UV-Optical detectors
- 2006: Develop Pathfinder Concept suitable for future Probe/Discovery-type opportunities and work with other NASA (e.g., ST-9) and ESA projects (e.g., EMMA, SMART-2/LISA-PF) to collaboratively develop relevant technologies
- ~2015: Fly pathfinder mission(s)
- ~2025: Fly full mission

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