The Stellar Imager (SI) “Vision Mission”:
Imaging the UV/Optical Universe with Sub-milliarcsecond Resolution

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and the SI Mission Concept Development Team

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

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Mission Concept Development Team

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

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

Institutional and topical leads from these institutions include:

Additional science and technical collaborators from these institutions include:

International Partners include:
- J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe
The Stellar Imager (SI) is a UV-Optical, space-based interferometer for 0.1 milli-arcsecond spectral imaging of stellar surfaces and interiors and of the Universe in general.

It will resolve for the first time the surfaces of sun-like stars and the details of many other astrophysical objects & processes, e.g.:

<table>
<thead>
<tr>
<th>Magnetic Processes in Stars</th>
<th>Cool, Evolved Giant &amp; Supergiant Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>activity and its impact on planetary climates</td>
<td>spatiotemporal structure of extended atmospheres, pulsation, winds, shocks</td>
</tr>
<tr>
<td>and on the origin and maintenance of life; stellar structure and evolution</td>
<td>Supernovae &amp; Planetary Nebulae</td>
</tr>
<tr>
<td>Stellar interiors</td>
<td>close-in spatial structure</td>
</tr>
<tr>
<td>in stars outside solar parameters</td>
<td>Interacting Binary Systems</td>
</tr>
<tr>
<td></td>
<td>resolve mass-exchange, dynamical evolution/accretion, study dynamos</td>
</tr>
<tr>
<td>Infant Stars/Disk systems</td>
<td>Active Galactic Nuclei</td>
</tr>
<tr>
<td>accretion foot-points, magnetic field structure &amp; star/disk interaction</td>
<td>transition zone between Broad and Narrow Line Regions; origin/orientation of jets; distances</td>
</tr>
<tr>
<td>Hot Stars</td>
<td></td>
</tr>
<tr>
<td>hot polar winds, non-radial pulsations, envelopes and shells of Be-stars</td>
<td></td>
</tr>
</tbody>
</table>

SI’s Primary Science Goals are 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
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Baseline (B)</td>
<td>100 – 1000 m (500 m typical)</td>
<td>Outer array diameter</td>
</tr>
<tr>
<td>Effective Focal Length</td>
<td>1 – 10 km (5 km typical)</td>
<td>Scales linearly with B</td>
</tr>
<tr>
<td>Diameter of Mirrors</td>
<td>1 - 2 m (1 m currently)</td>
<td>Up to 30 mirrors total</td>
</tr>
<tr>
<td>λ-Coverage</td>
<td>UV: 1200 – 3200 Å</td>
<td>Wavefront Sensing in optical only</td>
</tr>
<tr>
<td></td>
<td>Optical: 3200 – 5000 Å</td>
<td></td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>UV: 10 Å (emission lines)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UV/Opt: 100 Å (continuum)</td>
<td></td>
</tr>
<tr>
<td>Operational Orbit</td>
<td>Sun-Earth L2 Lissajous, 180 d</td>
<td>200,000x800,000 km</td>
</tr>
<tr>
<td>Operational Lifetime</td>
<td>5 yrs (req.) – 10 yrs (goal)</td>
<td></td>
</tr>
<tr>
<td>Accessible Sky</td>
<td>Sun angle: 70º ≤ β ≤ 110º</td>
<td>Entire sky in 180 d</td>
</tr>
<tr>
<td>Hub Dry Mass</td>
<td>1455 kg</td>
<td>Possibly 2 copies</td>
</tr>
<tr>
<td>Mirrorsat Dry Mass</td>
<td>65 kg (BATC) - 120 kg (IMDC)</td>
<td>For each of up to 30</td>
</tr>
<tr>
<td>Ref. Platform Mass</td>
<td>200 kg</td>
<td></td>
</tr>
<tr>
<td>Total Propellant Mass</td>
<td>750 kg</td>
<td>For operational phase</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>50 μas – 208 μas (@1200–5000Å)</td>
<td>Scales linearly ~ λ/B</td>
</tr>
<tr>
<td>Typical total time to image</td>
<td>&lt; 5 hours for solar type</td>
<td></td>
</tr>
<tr>
<td>stellar surface</td>
<td>&lt; 1 day for supergiant</td>
<td></td>
</tr>
<tr>
<td>Imaging time resolution</td>
<td>10 – 30 min (10 min typical)</td>
<td>Surface imaging</td>
</tr>
<tr>
<td>Seismology time res.</td>
<td>1 min cadence</td>
<td>Internal structure</td>
</tr>
<tr>
<td># res. pixels on star</td>
<td>~1000 total over disk</td>
<td>Solar type at 4 pc</td>
</tr>
<tr>
<td>Minimum FOV</td>
<td>&gt; 4 mas</td>
<td></td>
</tr>
<tr>
<td>Minimum flux detectable at</td>
<td>5.0 x 10^{-14} ergs/cm²/s integrated over C IV lines</td>
<td>10 Å bandpass</td>
</tr>
<tr>
<td>1550 Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precision Formation Fly.</td>
<td>s/c control to mm-cm level</td>
<td></td>
</tr>
<tr>
<td>Optical Surfaces Control</td>
<td>Actuated mirrors to μm-nm level</td>
<td></td>
</tr>
<tr>
<td>Phase Corrections</td>
<td>to λ/10 Optical Path Difference</td>
<td></td>
</tr>
<tr>
<td>Aspect Control/Correct.</td>
<td>3 μas for up to 1000 sec</td>
<td>Line of sight maintenance</td>
</tr>
</tbody>
</table>
What Will Stellar Imager See?

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

Model

*SI* images

Baseline: 125m  250m  500 m

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

Model

*SI* image (2mas dia)

Baseline: 500 m

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

*SI* simulation in Ly $\alpha$-fluoresced H2 lines

Baseline: 500 m

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

*SI* simulations in CIV line

(model)  (500 m baseline)

0.1 mas  0.1 mas
Required Capabilities for SI

- Wavelength coverage: 1200 – 5000 Å
- access to UV emission lines from Ly α 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)
  - ~10-Å UV pass bands, 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 time 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 dwarf stars
- enable energy resolution/spectroscopy of detected structures
- a long-term (~ 10 year) mission to study stellar activity cycles:
  - individual telescopes/hub(s) can be refurbished or replaced
“Strawman” Concept

- 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
The Stellar Imager Vision Mission

SI Cross-Sectional Schematic

30 real 1m, Primary Mirrors with Curvature of 12 microns over 0.5m Formed using Actuators to Match Curvature of Virtual Parabola

Primary Mirrors to Hub ~ 5000 m

Outer Diameter of Light Collecting Primary Mirror Array ~ 500 m

Mirrors Aligned to Form a Three Dimensional Parabolic Surface

(curvature: 3.125m in 250m, from center to outer most mirror)

(not to scale)
Principal Elements of SI Hub

- Entrance Baffle Plate
- 30 Redirector Flats (mini-Golomb Array, 10 mm Diam. Each)
- Secondary Mirror (6x6 cm, under baffle plate)
- Science & Phasing Detector Arrays
- Hub Spacecraft Bus
- 30 Laser Ranging Units (one for each Mirrorsat)
- Stiffening Rings (in telescope tube assembly)
- Thermal Equalizer Rings
- Stewart Vibration Isolation Truss
Top Technological Challenges and Enabling Technologies

- **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 control to 10’s of micro-arcsec
  - positioning mirror surfaces to 2 nm
  - variable, non-condensing, continuous micro-Newton thrusters

- **precision metrology** (2 nm over multi-km baselines)
  - multiple modes to cover wide dynamic range

- **wavefront sensing and real-time, autonomous analysis**

- **methodologies for grd.-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 (perhaps using deformable UV quality flats)
  - larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)
The GSFC Fizeau Interferometer Testbed (FIT): Developing Closed-Loop Optical Control for Large Arrays


- A ground-based testbed which will
  - explore principles of and requirements for Stellar Imager & other Fizeau Interferometer/Sparse Aperture Telescopes (e.g. MAXIM, LF, PI), enable their development, reduce technical and cost risks
  - utilize 7-18 separate articulated apertures, with tip, tilt, and piston automatically controlled on each
  - validate new and existing analytic and computational models to ensure realistic performance assessment of future flight designs
  - demonstrate closed-loop control of system based on analysis of science data stream
  - evaluate and demonstrate performance of new and existing image synthesis algorithms and successful image reconstruction from actual laboratory sparse aperture/interferometric data
The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT):

K. Carpenter, R. Lyon, K. Hartmann/GSFC; P. Stahl/MSFC, D. Miller/MIT,
J. Marzouk/Sigma Space, D. Mozurkewich/Seabrook Eng.

A ground-based testbed which will

- In combination with FIT enable synergistic development of technologies needed to support space-borne synthetic aperture ultra-high resolution imaging
- Develop and demonstrate algorithms for autonomous precision formation flying which can, in the future, be combined with higher precision optical control systems
- Set requirements for future staged-control systems
- Be created at relatively low cost by utilizing equipment from existing MIT-developed SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) experiment on the MSFC Flat Floor Facility
- Areas of investigation include:
  - Formation Capture (deployment)
  - Formation Maintenance
  - Formation Reconfiguration
  - Synthetic Imaging maneuvers (retargeting and reconfig.)
SI Status

- SI in NASA SEC (now SSSC) Roadmap since 2000
- SI selected for further concept development by the NASA HQ 2003 Vision Mission NRA review
- Major Partnerships established with LMATC, SAO, BATC, NGST, JPL, CU to develop concept/technology
- Phase I of the Fizeau Interferometry Testbed (FIT) has begun operation to develop closed-loop optical control of a multi-element array
- GSFC Integrated Mission Design Center (IMDC) and Instrument Synthesis and Analysis Lab (ISAL) studies executed (10/2004; 2/2005) to produce a system design & technology development roadmap
- SI presented to SEU/Origins, SSSC, APIO, Universe Roadmap Committees (Nov. 2005)
- In the May, 2005 NASA Strategic Roadmaps, SI is included as
  - A “Flagship” (Vision) mission in the SSSC Roadmap
  - A candidate “Pathways to Life Observatory” in the EUD Roadmap
Summary: Stellar Imager (SI) Vision Mission

- UV-Optical Interferometer to provide 0.1 mas imaging (+ spectroscopy) of
  - magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, transport processes on many scales in Universe
- 20-30 “mirrorsats” formation-flying with beam combining hub
- Launch ~ 2024, to Sun-earth L₂
- maximum baseline ~500 m
- => 1000 pixels/stellar image
- Mission duration: ~10 years

Prime Science Goals

image surface/sub-surface features of distant stars; measure their spatial/temporal variations to understand the underlying dynamo process(es)

improve long-term forecasting of solar and stellar magnetic activity

understand the impact of stellar magnetic activity on planetary climates and life

understand transport processes controlled by magnetic fields throughout the Universe

perform high angular resolution studies (imaging + spectroscopy) of Active Galactic Nuclei, Quasars, Supernovae, Interacting Binary Stars, Forming Stars/Disks

http://hires.gsfc.nasa.gov/~si
Extra slides
Development of Space Interferometry

- **SIM**
  - Precision Metrology
  - Boom Interferometer
  - TPF Targeting

- **ST-9 or Smart-3**
  - Precision Formation Flying
  - Possible Interferometry

- **Grd-Based Testbeds**
  - Wavefront Sensing/Control: FIT, STAR9
  - Formation Flying: SIFFT, FFTB, FCT

- **Ground-based interferometry**
  - (Keck, VLTi, LBT)
  - Giant star imaging
  - Binary stars

- **TPF-I/Darwin**
  - Planet Detection, Spectroscopy
  - Free-flying IR Nulling Interferom.
  - 0.75 mas; PI & LF Targeting

- **SI Pathfinder**
  - UV/Optical Interferometry
  - Formation Flying

- **Stellar Imager**
  - Stellar dynamos
  - UV/Optical Interferom.< 0.1 mas resolution

- **Black Hole Imager**
  - X-ray Interferom.

- **Life Finder**
  - Searching for Signs of Life

- **Planet Imager**
  - Terrestrial-Planet Imaging

Timeline:
- 2005
- 2010
- 2015
- 2020
- 2025 +
SI and the NASA-ESA Strategies

- **SI** addresses the origins & evolution of structure & life in the Universe, and specific science goals of 3 research Themes in the NASA SMD:
  - learn how galaxies, stars, planetary systems form & evolve (Origins/EUD)
  - understand development of structure/flows of magnetic fields (SEU/EUD)
  - understand origins & societal impacts of variability in Sun-Earth System (SSSC)

- **SI** complements the planetary imaging interferometers:
  - *Terrestrial Planet Finder-I (TPF-I)/Darwin* and *Planet Imager* null the stellar light to find and image planets
  - *Stellar Imager* images the central star to study the effects of that star on the habitability of planets and the formation of life on them.

- **SI** is on the strategic path of NASA Origins interferometry missions and is a stepping stone towards crucial technology…
  - comparable in complexity to the *Terrestrial Planet Finder-I*
  - will serve as technological & operational pathfinder for *Life Finder (LF) and Planet Imager (PI)*

TPF/Darwin, SI, LF, and PI together provide complete views of other solar systems.
Stellar Imager and the President’s Vision

*SI* fits into the President’s Exploration Initiative in 2 distinct arenas:

1) **as one of the “deep-space observatories” which will be a part of the search for and study of habitable planets around other stars.**

   Stellar Imager (SI) is an essential part of this mandate since it enables the assessment of the impact of stellar magnetic activity on the habitability of planets found by the planet search and imaging missions (e.g., TPF and Planet Imager (PI)).

2) **as a means to improve our ability to forecast space weather within our own solar system:**

   Exploration requires that we know space weather throughout much of the heliosphere, and that means we need long-term forecasts of solar activity, which in turn requires a fundamental understanding of the solar dynamo and of all related transport processes. The Living With a Star initiative addresses that on the fairly short term, while the Stellar Imager is to provide the knowledge (constraints from a broad population of stars of differing activity level) critically needed to test and validate models developed under the LWS program.
Precursor/Pathfinder Mission

- A pathfinder mission which takes smaller technological steps is desirable to reduce mission risk and would
  - advance technologies needed for other missions in NASA strategic plans
  - will address a subset of the SI science goals

Desirable characteristics of a pathfinder mission
- possible within a decade
- uses a modest number of free-flying spacecraft (3-5)
- operates with modest baselines (~ 50 m)
- performs beam combination with ultraviolet light
- produces UV images via imaging interferometry and enable significant new science

- Such a mission with a small # of spacecraft
  - requires frequent reconfigurations and limits observations to targets whose variability does not preclude long integrations
  - tests most of the technologies needed for the full-size array