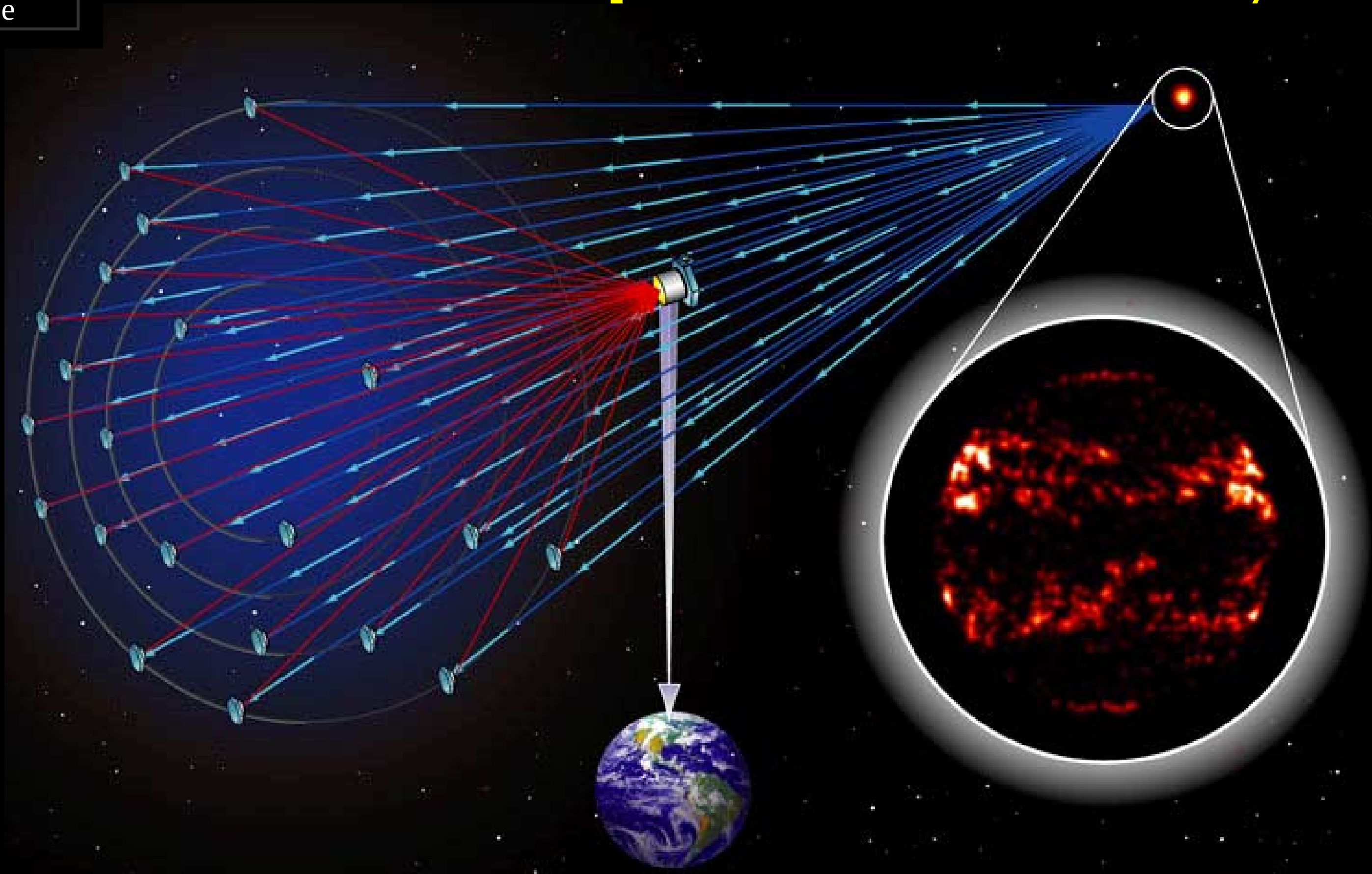
The *Stellar Imager* (*SI*): An Ultra-High Angular Resolution UV/Optical Observatory

Goddard Space
Flight Center



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Mission Concept Development Team

- Mission concept under development by NASA/GSFC in collaboration with LMATC, NRL/NPOI, STScI, UMD...
  - NASA-GSFC: Ken Carpenter (Study Lead), Rick Lyon (Testbed Lead), Joe Marzouk/Sigma, Greg Solyar/UMBC, Xiaolei Zhang/SSAI, Lisa Mazzuca, Bill Danchi, Susan Neff
  - LMMS/ATC: Carolus Schrijver (Science Lead)
  - NRL/NPOI: Tom Armstrong, Dave Mozurkewich, Tom Pauls
  - STScI: Ron Allen, Jay Rajagopal
  - UMD: Lee Mundy
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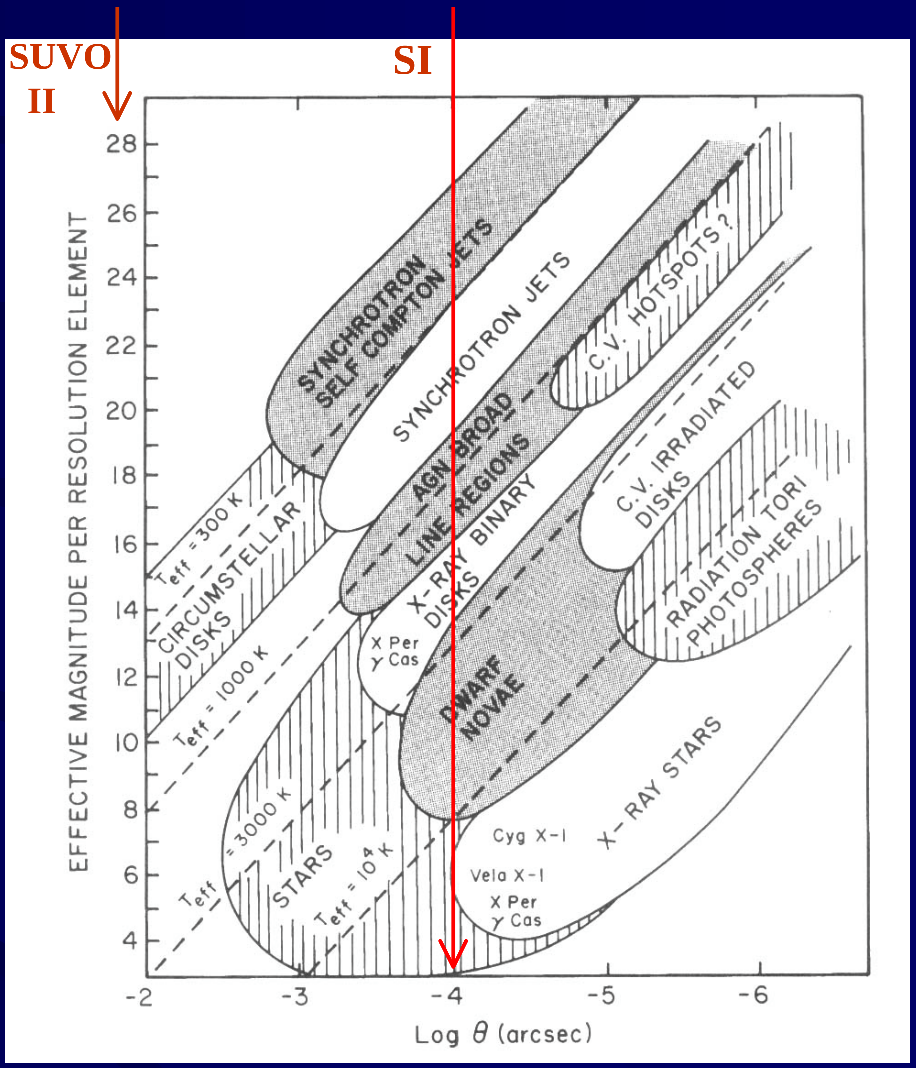
The Need for Interferometry

- the true nature of many astrophysical objects lies hidden within the 1-D point source observations possible with plausible size monolithic or segmented mirrors
- even very large monolithic telescopes, e.g. 8-m SUVO Class II, cannot provide required resolution
- 0.5 - 1.0 km baseline imaging interferometers can provide orders of magnitude advance in angular resolution



Begelman (1991)

A long-baseline UV-optical interferometer in space would benefit many fields of astrophysics

Stellar Magnetic Activity and Internal Structure

surface imaging & asteroseismology:

understand solar/stellar dynamo, enable improved forecasting of magnetic activity and its impact on astrobiology & life

internal structure, including, e.g., opacities, in stars outside solar parameters

Active Galactic Nuclei

transition zone between BLR & NLR, origin/orientation of jets

Quasi-stellar Objects & Black Holes

close-in structure, especially radiation from accretion processes

Supernovae

close-in spatial structure

Hot Stars

hot polar winds, non-radial photospheric pulsations, envelopes and shells of Be-stars

Spectroscopic binary stars / apparently single stars

observe companions & orbits, determine stellar properties, perform key tests of stellar evolution, check putative planetary systems for stellar binarity

Interacting Binary Stars

resolve mass-exchange, dynamical evolution/accretion, study more efficient dynamos

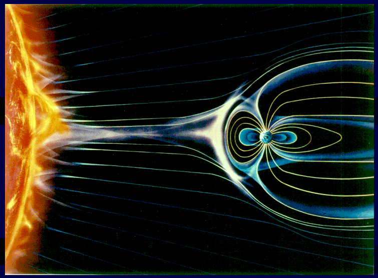
Cool, Evolved Giant & Supergiant Stars, LPV/SRV's

spatiotemporal structure of extended atmospheres/winds, shocks

Science Context for *SI*: The Importance of Understanding Stars and Stellar Dynamos

- The Sun is only one of many classes of stars, but our close-up view of the Sun has enabled discoveries that have revolutionized physics and astrophysics time and again
  - existence of helium, role of nuclear fusion, convective envelopes, interior structure by acoustic sounding, neutrino deficit
  - importance of non-linear, non-local processes (radiation, magnetic dynamo, convection, global circulation)
- The Dynamo is an ensemble of electric currents flowing in the subsurface layers of a star. It produces a complex magnetic field topology and induces associated activity which makes stars (including the sun) ever-changing and "dynamic". That magnetic field:
  - slows the rotation of the collapsing cloud, enabling star formation
  - couples evolution of star and pre-planetary disk
  - results in energetic radiation conducive to the formation (& destruction) of complex molecules
  - governs the habitability of the biosphere through space weather and its effect on planetary climate through variations it induces in luminosity, wind, and radiation
- Understanding stars and the dynamo process in general is the foundation for understanding the Universe

Stellar Activity is Key to Understanding Life in the Universe and Earth's habitability
BUT
There is no comprehensive model of solar/stellar magnetic activity!



- Major progress requires a detailed understanding of the stellar dynamo and its behavior in time and with stellar parameters
- The *Stellar Imager (SI)* is a large space-based UV-optical interferometer designed for high angular resolution which will
  - zoom in on "point sources" so they turn into objects that can be imaged in detail, thereby opening up an entire new realm of science
  - reveal processes no one has seen before, thereby driving theoretical developments in a host of fields
  - provide a tool to astrophysicists of the same fundamental nature as the microscope to biologists

Primary Science Goals

- Study spatial and temporal stellar magnetic activity patterns in a sample of stars covering a broad range of activity level, in order to understand the underlying dynamo process(es) and thereby
  - enable improved forecasting of solar activity on time scales of days to centuries, including Maunder-like minima and “grand maxima” that significantly affect geospace and earth’s weather
  - understand the impact of stellar magnetic activity on astrobiology & life
- Enable asteroseismology (acoustic imaging) to measure internal stellar structure and rotation and their relationship to the dynamo
- Complete the assessment of external solar systems
  - image the central stars of systems for which the Origins IR-interferometry missions find and image planets, and determine the impact of the activity of those stars on the habitability of the surrounding planets

Science Requirements

- A Population study of cool stars
  - To understand the dynamo, we need to know how magnetic fields are generated & behave in different circumstances - the sun is only one example and provides insufficient constraints on theories of dynamos, turbulence, structure, and internal mixing
    - we must observe other stars to *establish how mass, rotation, brightness and age affect the patterns of activity* & determine:
      - What determines cycle strength and duration? Can multiple cycles exist at the surface? How do polar spots form?
      - How common is solar-like activity? What are extremely (in)active stars like? What are Maunder-minimum states like?
- Asteroseismology (acoustic imaging) to look beneath surface
  - Although its clearest manifestations are visible on the stellar surface, a full understanding of the dynamo requires a knowledge of the underlying layers
    - Where is the seat of the dynamo? What determines differential rotation and meridional circulation, and what role do they play in the dynamo?
    - What is the impact of magnetic deceleration on internal rotation and stellar evolution? How are stellar interiors modified in extremely active stars?

Primary Performance Goals

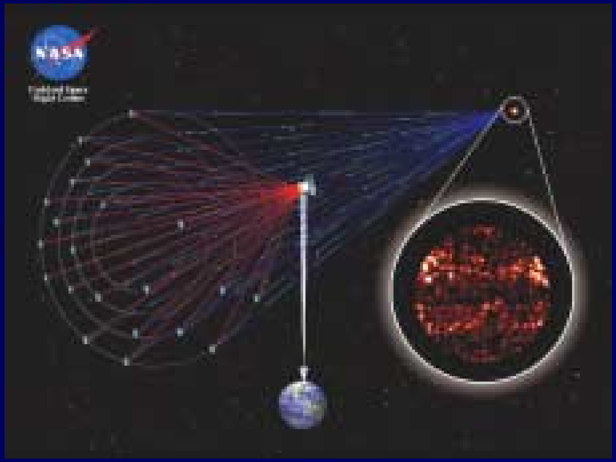
- Obtain surface images of stars with different activity levels
  - for a substantial sample of nearby dwarf and giant stars, obtain a resolution of order 1000 total pixels (33x33) (~50,000 km on a Sun-like star at 4 pc)
  - study a sample in detail, revisiting over many years
  - measure:
    - sizes, lifetimes, and emergence patterns of stellar active regions
    - surface differential rotation, field dispersal by convective motions, and meridional circulation
    - directly image the entire convection spectrum on giant stars, and the supergranulation on, e.g., the solar counterpart α Cen
- Obtain acoustic images of the sub-surface layers of stars, using low to intermediate degree non-radial modes to measure internal stellar structure & rotation
  - requires high time resolution, long-duration observations on selected targets

Design Requirements

- Requirements for imaging of stellar surface activity
  - UV images: for visibility of surface manifestations of dynamo
    - dark starspots in visible-light photosphere are small in most stars and have low contrast with surrounding bright stellar surface
    - ideal activity diagnostics are high-contrast bright spots seen in UV (chromospheric, transition-layer) emission (Mg II h&k 2800 A, C IV 1550 A) from plages above surface wherever it is penetrated by strong magnetic fields
    - modest integration times (~ hours for dwarfs to days for giants) to avoid smearing of images due to rotation, activity evolution, & proper motions.
- Requirements for imaging of stellar interiors by seismology
  - Short integration times (minutes for dwarf stars to hours for giant stars)
    - requires broadband optical wavelengths to get sufficiently high fluxes
  - Low-resolution imaging to measure non-radial resonant waves
    - 30-100 total resolution elements sufficient
- Flexible interferometer configuration required for image synthesis

Strawman *Stellar Imager (SI)* Mission Concept

- a 0.5 km diameter space-based UV-optical Fizeau Interferometer
  - located near the sun-earth L2 point to enable precision formation flying
- a reconfigurable array of 10-30 one-meter-class spherical mirrors
  - those “mirrorsats” direct light to an image-plane beam combination facility in a hub at the prime focus
- it will provide:
  - an angular resolution of 60 and 120 micro-arcsec at 1550 Å and 2800 Å
  - ~ 1000 pixels of resolution over the surface of nearby dwarf stars
  - observations in
    - ~10-Ångstrom UV pass bands around, e.g., C IV (100,000 K), Mg II h&k (10,000 K)
    - broadband, near-UV or optical continuum (formed at 3,000-10,000 K)
  - a long-term (> 10 year) mission to study stellar activity/magnetic cycles:
    - individual telescopes/central hub can be refurbished or replaced as needed



Simulated Stellar Images

Interferometric images in the light of CIV (1550 A) of a sun-like star at 4 pc, viewed equator-on. These simulations were computed with SISIM (Allen & Rajagopal, STScI) using the input model solar image shown in the bottom right and assuming 250 and 500 meter maximum baseline arrays. The first two rows assume a Y-shaped configuration set in the indicated number of rotational positions. The 1st two images in the last row assume 30 elements arranged in a low-redundancy "Golomb rectangle" (Golomb & Taylor, IEEE Trans. Info. Theo., 28, #4, 600, 1982). The first two columns in all cases show "snapshots" taken without rotating the arrays.

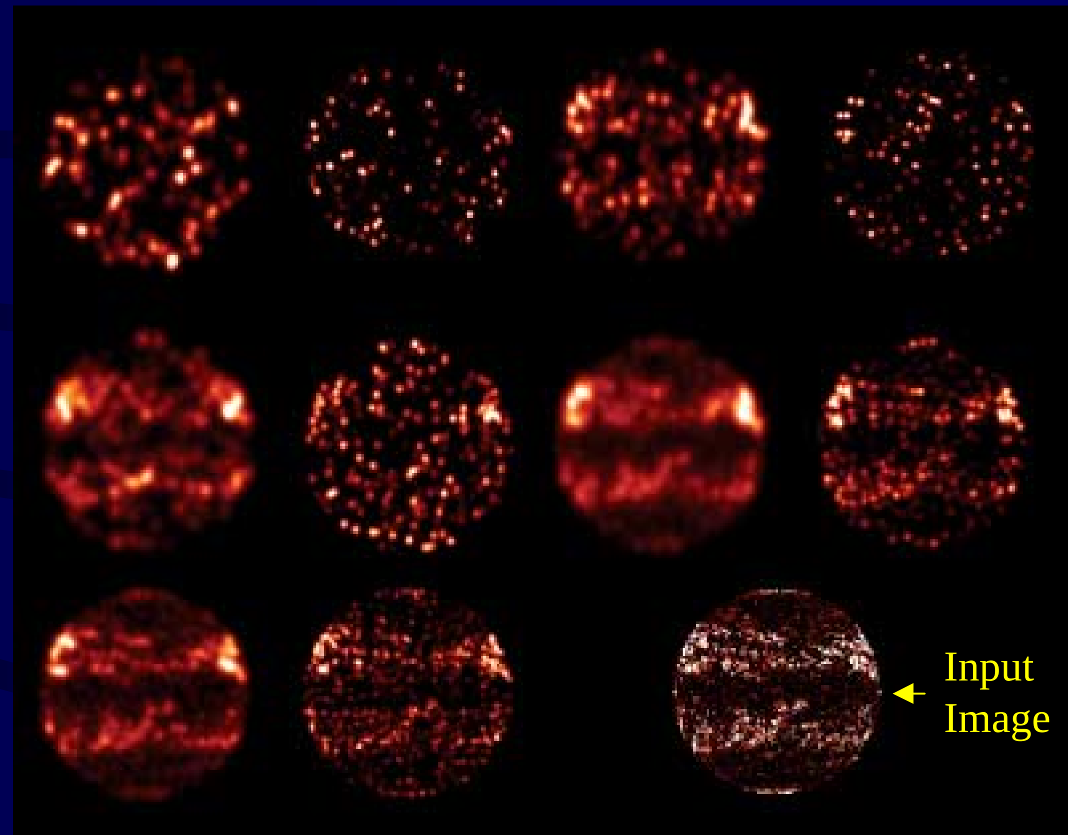
rotations(step size): 0 (0) 24 (15deg)

elements

6

12

30



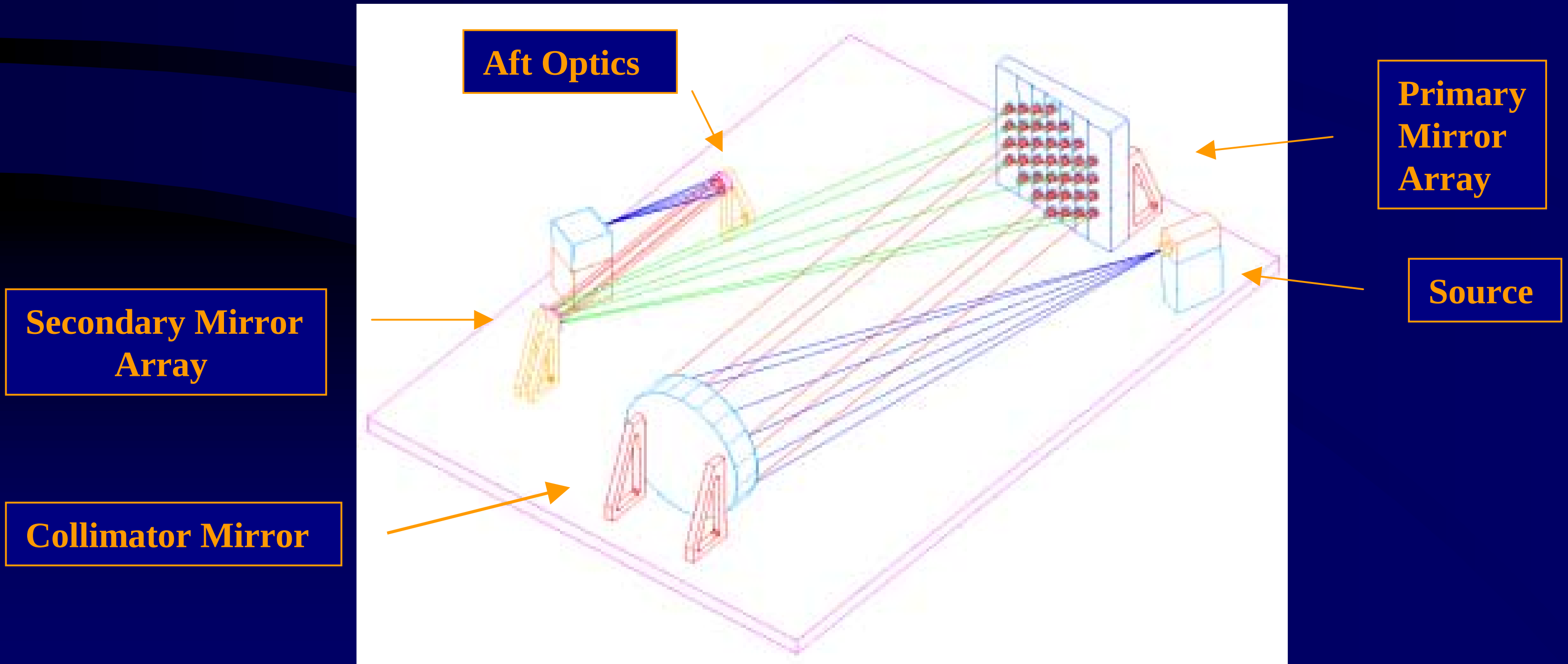
Baselines: 250 m 500 m 250 m 500 m

"Snapshots" (no rotations) (24 array rotations)

Conclusion: 30 static elements appear to be sufficient to adequately synthesize this stellar image, although 1 rotation of this array ought to improve things substantially still. Alternatively, fewer elements can be used with a larger number of rotations (6 elements/24 rotations or 12 e/6 r).

The Fizeau Interferometer Testbed (FIT)

- A ground-based laboratory testbed at GSFC for UV-Optical Fizeau Interferometers / Sparse Aperture Telescopes
  - designed to explore the principles of and requirements for the Stellar Imager mission concept and other Fizeau Interferometers/Sparse Aperture Telescope missions
  - utilizes a large number of truly separate, articulated apertures (each with 5 degrees of freedom: tip, tilt, piston, 2D translation of array elements) in a sparse distribution
  - has the long-term goal of demonstrating closed-loop control of articulated mirrors and the overall system to keep beams in phase and optimize imaging
  - enables critical assessment of various image reconstruction algorithms (phase diversity, clean, MEM, etc.) for utility and accuracy by application to real data



Place in NASA/ESA Strategic Roadmaps

- ***SI*** is on strategic path of NASA Origins interferometry missions
  - it is a stepping stone towards crucial technology…
    - ***SI*** is comparable in complexity to the interferometer option for ***Terrestrial Planet Finder***, and it can serve as a useful technological and operational pathfinder for the ***Planet Imager***: ***SI*** resolution is ~40x less demanding than ultimate NASA goal
  - … while addressing science goals of 3 NASA/OSS research Themes
    - understand why the sun varies (SEC)
    - understand the origin of stars, planetary systems, and life (Origins)
    - understand the structure and evolution of stars (SEU)
  - it is complementary to the planetary imaging interferometers
    - ***Terrestrial Planet Finder***, ***IRSI/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.
    - ***TPF, SI, IRSI/Darwin,*** and ***PI*** together provide complete views of other solar systems

Precursor/Pathfinder Mission(s)

- The path to a large-baseline UV-optical interferometer in space is long and difficult - one or more pathfinder missions which take smaller technological steps and produce science results within the career-spans of current-day astronomers are desirable
  - TPF may not be an interferometer, STARLIGHT may not fly
  - SIM does not use the free-flying formations that will be needed for truly long-baseline facilities and it will operate only at longer wavelengths
- Useful concepts that should be considered include
  - An early mission using booms and modest baselines but performing beam combination with Ultraviolet light and producing UV images
  - An intermediate mission using a small number of separate precision-formation-flying spacecraft
    - the small # of spacecraft would require frequent reconfigurations and limit observations to targets whose variability does not preclude long integrations but such a mission would test most of the technologies needed for the full-size array
    - the addition of high-resolution spectroscopy to such a mission would increase the science return significantly at modest cost

Current Status

- Included in far-horizon NASA "Sun-Earth Connection" Roadmap
- Mission concept continues to be developed by NASA/GSFC in collaboration with LMATC, NRL/NPOI, STScI, UMD, etc.
- Web site created: **http://hires.gsfc.nasa.gov/~si**
  - "white paper", science and concept presentations available for download
- Recent events
  - Requirements defined, detailed design in progress for Laboratory Fizeau Interferometry Testbed (FIT) at GSFC
  - Initial GSFC Integrated Mission Design Center (IMDC) Study performed
- Next Steps
  - Continue Architecture Trade/Feasibility Studies
  - Test/demonstrate design concepts with ground-based testbed (the FIT)
    - assess/refine technical requirements on hardware and control algorithms
    - demonstrate closed-loop control of array elements to phase array
    - evaluate image reconstruction algorithms using real data (generated by testbed)
  - Gather & utilize additional community input and produce book summarizing science/societal motivations for mission, technology roadmap, and most promising architecture options