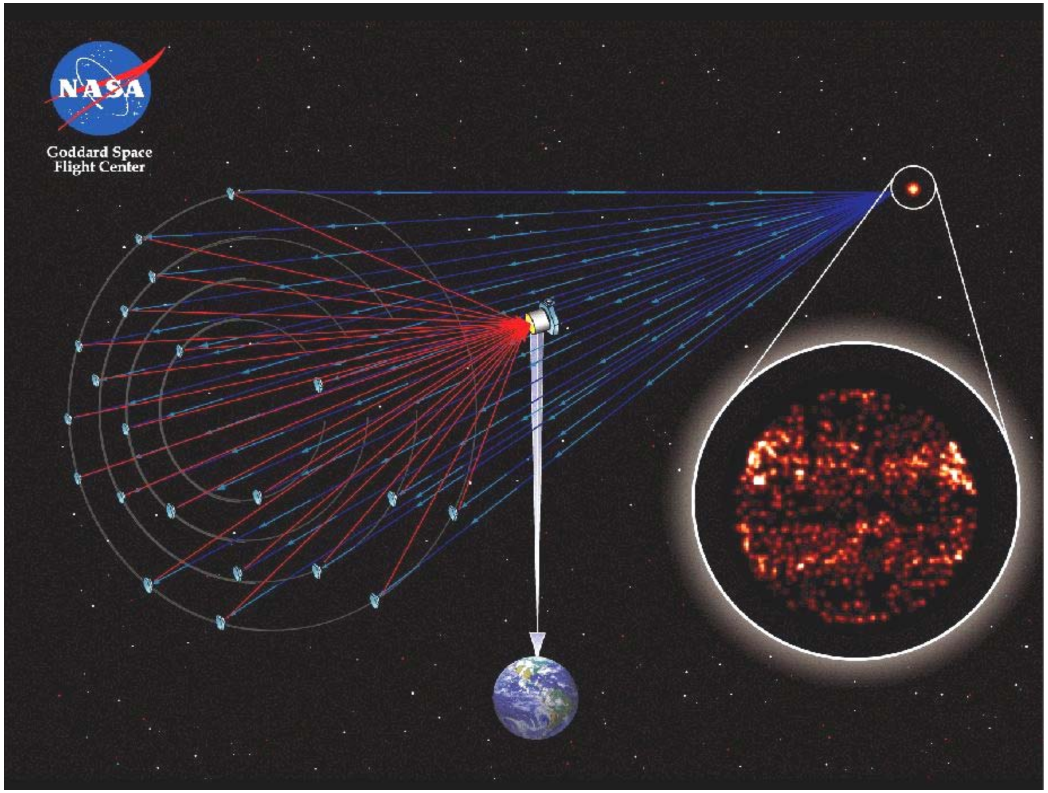
The Stellar Imager (*SI*) – A Mission to Resolve Stellar Surfaces, Interiors, and Magnetic Activity



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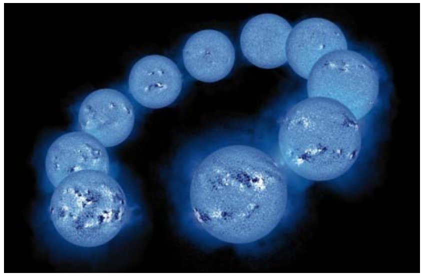
URL: http://hires.gsfc.nasa.gov/si/

Presented at the 2010 SOHO/GONG Meeting in Aix-en Provence

Why Stellar Imager?



- **Magnetic fields**
  - affect the evolution of structure in the Universe and
  - drive stellar activity which is key to life's origin and survival
- **But our understanding of how magnetic fields form and evolve is currently very limited**
  - our close-up look at the Sun has enabled the creation of approximate dynamo models, but none predict the level of magnetic activity of the Sun or any other star
- **Major progress requires understanding stellar magnetism in general and that requires a population study**
  - we need maps of the evolving patterns of magnetic activity, and of subsurface flows, for stars with a broad range of masses, radii, and activity levels
- **This understanding will, in turn, provide a major stepping stone toward deciphering magnetic fields and their roles in more exotic, complex, and distant objects**

Science goals of the Stellar Imager

- To understand
  - *Solar and Stellar Magnetic Activity* and their impact on *Space Weather, Planetary Climates, and Life*
    - the internal structure and dynamics of magnetically active stars
    - how magnetic activity drives all aspects of “space weather”, and how that affects planetary climates and life
  - general *Magnetic Processes* and their roles in the *Origin & Evolution of Structure* and in the *Transport of Matter* throughout the Universe.
- By
  - spatially resolving stellar disks to map the evolving atmospheric activity as a tracer of dynamo patterns
  - asteroseismic probing of internal stellar structure and flows (at least to degrees of order 60)
  - resolving the details of many astrophysical processes for the first time and transforming still images into evolving views of stellar surfaces, interacting binaries, supernovae, AGN, and a variety of targets in the distant Universe.

Science goals of the Stellar Imager (2)

- **In particular, we will develop and test a predictive dynamo model for the Sun by:**
  - *observing the patterns in surface magnetic activity for a large sample of Sun-like stars* (with ~1000 res. elements on surfaces of nearby stars)
  - *imaging the structure and differential rotation of stellar interiors* via asteroseismology with over 30 resolution elements on stellar disks
  - *carrying out a population study of Sun-like stars* to determine the dependence of dynamo action on mass, internal structure, flow patterns, and time. This will enable testing of dynamo models over a few years of observations of many stars, instead of over many decades using only the Sun.

Solar-type dynamos/Astrophysical Magnetic Fields: Key Questions

- what sets the dynamo strength and pattern?
- how active stars can form polar spots?
- what to expect next from the Sun, on time scales from hours to centuries?
- what causes solar-type ‘Maunder minima’ or ‘grand maxima’?
- why 2 in 3 Sun-like stars show no cycles?

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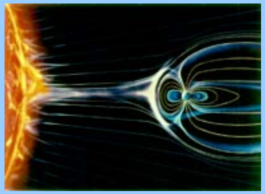

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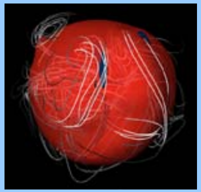

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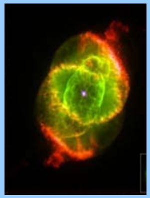
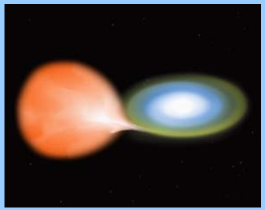


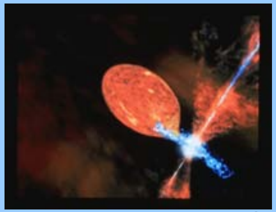
The cradle of life **Stellar activity & planets, life** **Dying giants**

How does the dynamo evolve?

The Sun



Interacting binary



Accretion, jets, outflows

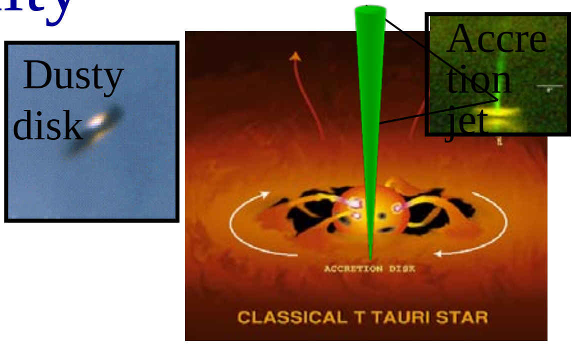
Accreting AGN

Can we generalize stellar dynamo properties?

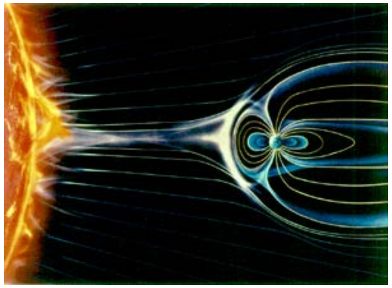
Science Driver: Stellar Activity is Key to Understanding Life in the Universe and Earth's habitability

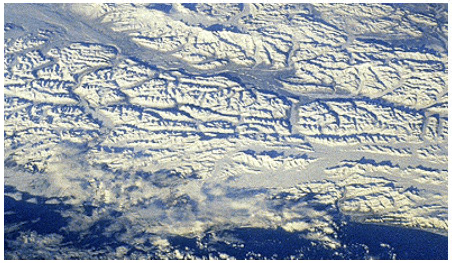
The stellar magnetic field

- 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 **planetary climate** through luminosity, wind, magnetic fields, and radiation

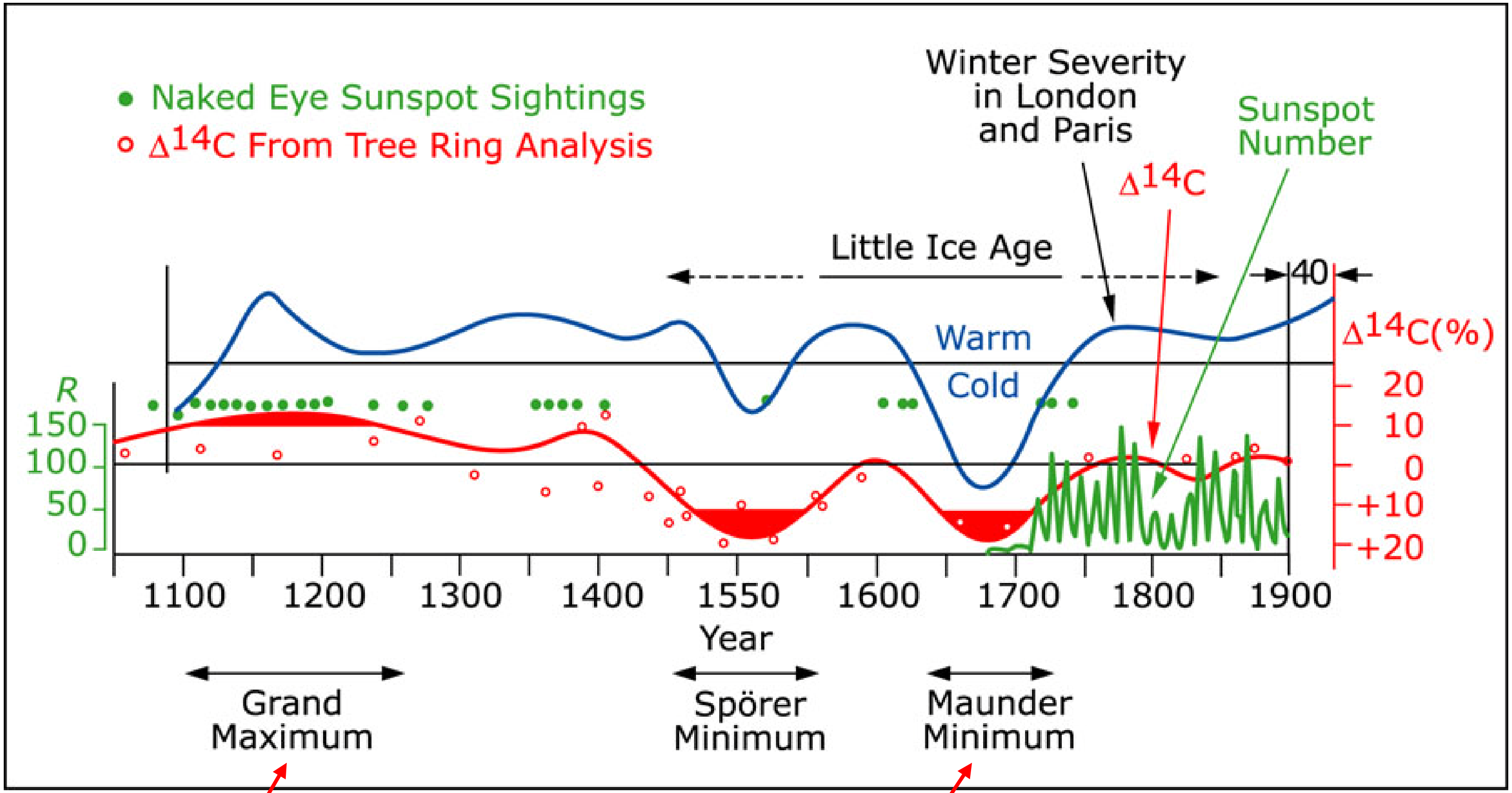


Star/Planet Formation


Space Weather


Climate Change

Effects of Solar Variations



"global warming",
aggravating greenhouse effect

crop failures,
July skating on the Thames

short-term effects:
disable satellites & power grids,
increase pipeline corrosion,
endanger astronauts

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 and interiors of sun-like stars and the details of many other astrophysical objects & processes, e.g.:

Magnetic Processes in Stars
activity and its impact on planetary climates and on the origin and maintenance of life;
stellar structure and evolution

Stellar interiors
in solar and non-solar type stars

Infant Stars/Disk systems
accretion foot-points, magnetic field structure & star/disk interaction

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

Cool, Evolved Giant & Supergiant Stars
spatiotemporal structure of extended atmospheres, pulsation, winds, shocks

Supernovae & Planetary Nebulae
close-in spatial structure

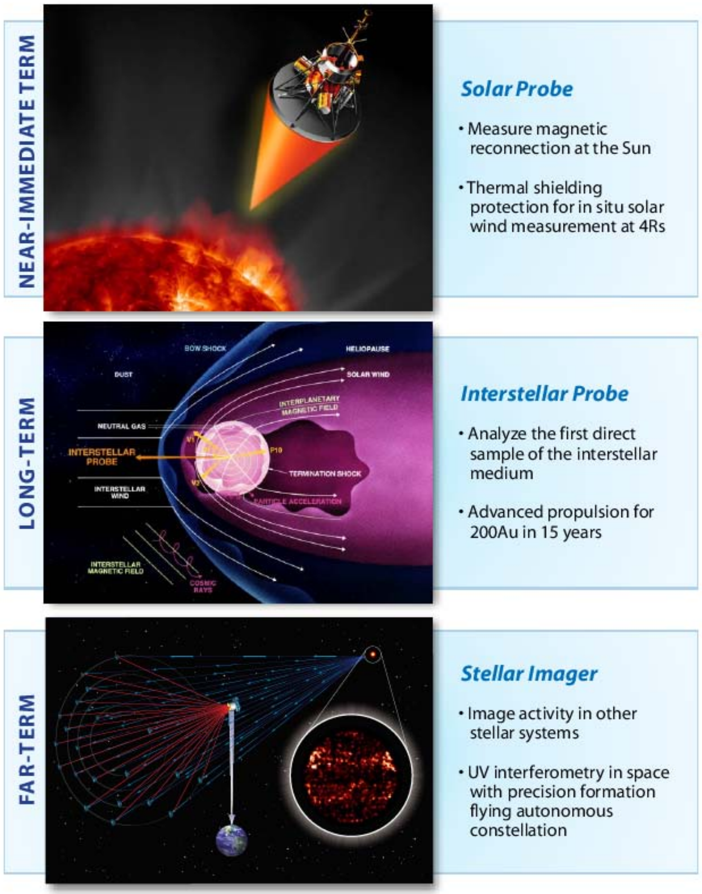
Interacting Binary Systems
resolve mass-exchange, dynamical evolution/accretion, study dynamos

Active Galactic Nuclei
transition zone between Broad and Narrow Line Regions;
origin/orientation of jets;
distances

Stellar Imager is a cross-theme mission addressing Science Goals of both the NASA *Heliophysics* and *Astronomy and Physics* Divisions

- In the Long-Term NASA Strategic Plan, SI is a:
  - "Flagship and Landmark Discovery Mission" in the 2005 Heliophysics Roadmap
  - Potential implementation of the UVOI in the 2006 Science Program for the Astronomy and Physics Division.
  - Candidate Large Class Strategic Mission for the mid-2020's.

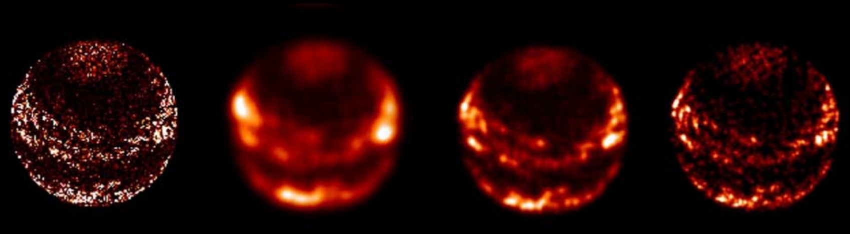
Heliophysics Division
Landmark Discovery Missions



What Will Stellar Imager See?

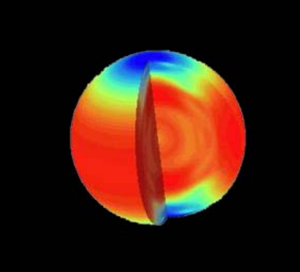
Solar-type star at *4 pc* in *CIV line*

Model　　*SIsim* images



Baseline: 125m　　250m　　500 m

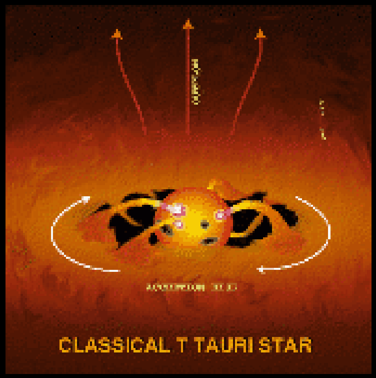
Asteroseismic mapping of internal structure, rotation and flows



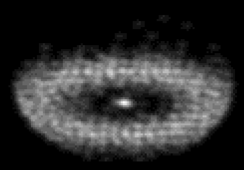
Resolution requirements:

- ~20,000km in depth
- modes of degree 60 or higher
- ~1 min. integration times

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



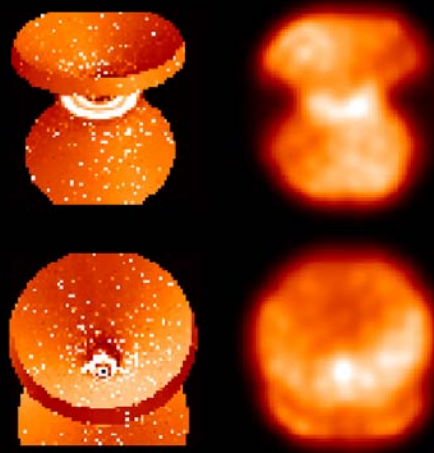
0.1 mas



SI simulation in
Ly α–fluoresced H2 lines

Baseline: 500 m

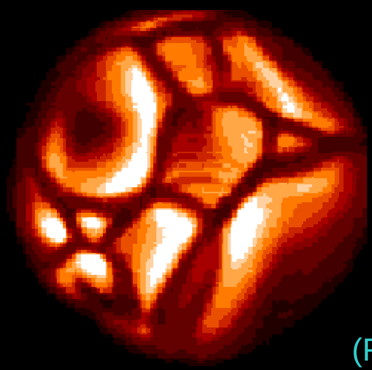
SI imaging of nearby AGN will differentiate between possible BELR geometries & inclinations



0.1 mas

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

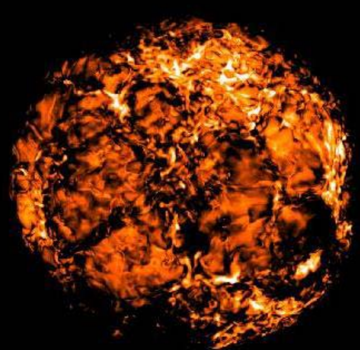
Betelgeuse (d ~ 0.2 kpc)



(Freytag/CRAL-ENS & Uppsala Univ.)

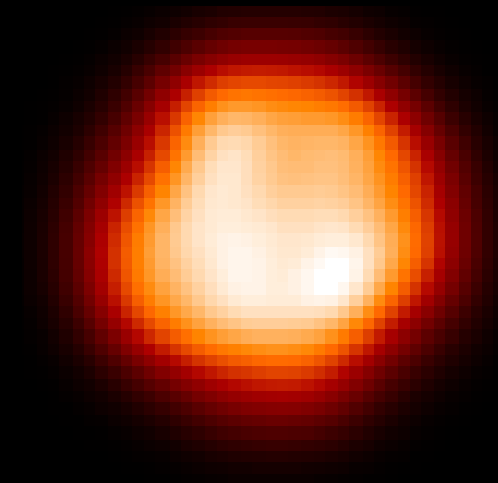
40mas

Mira (d ~ 0.2 kpc)

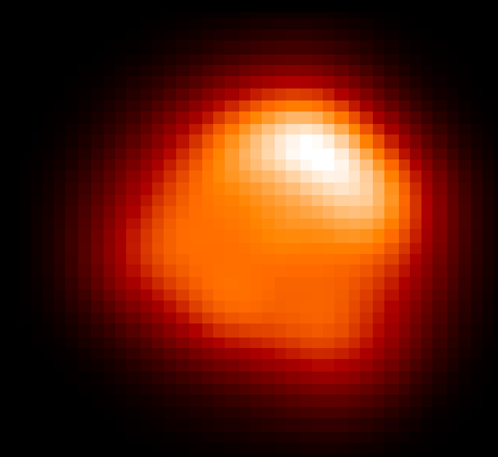


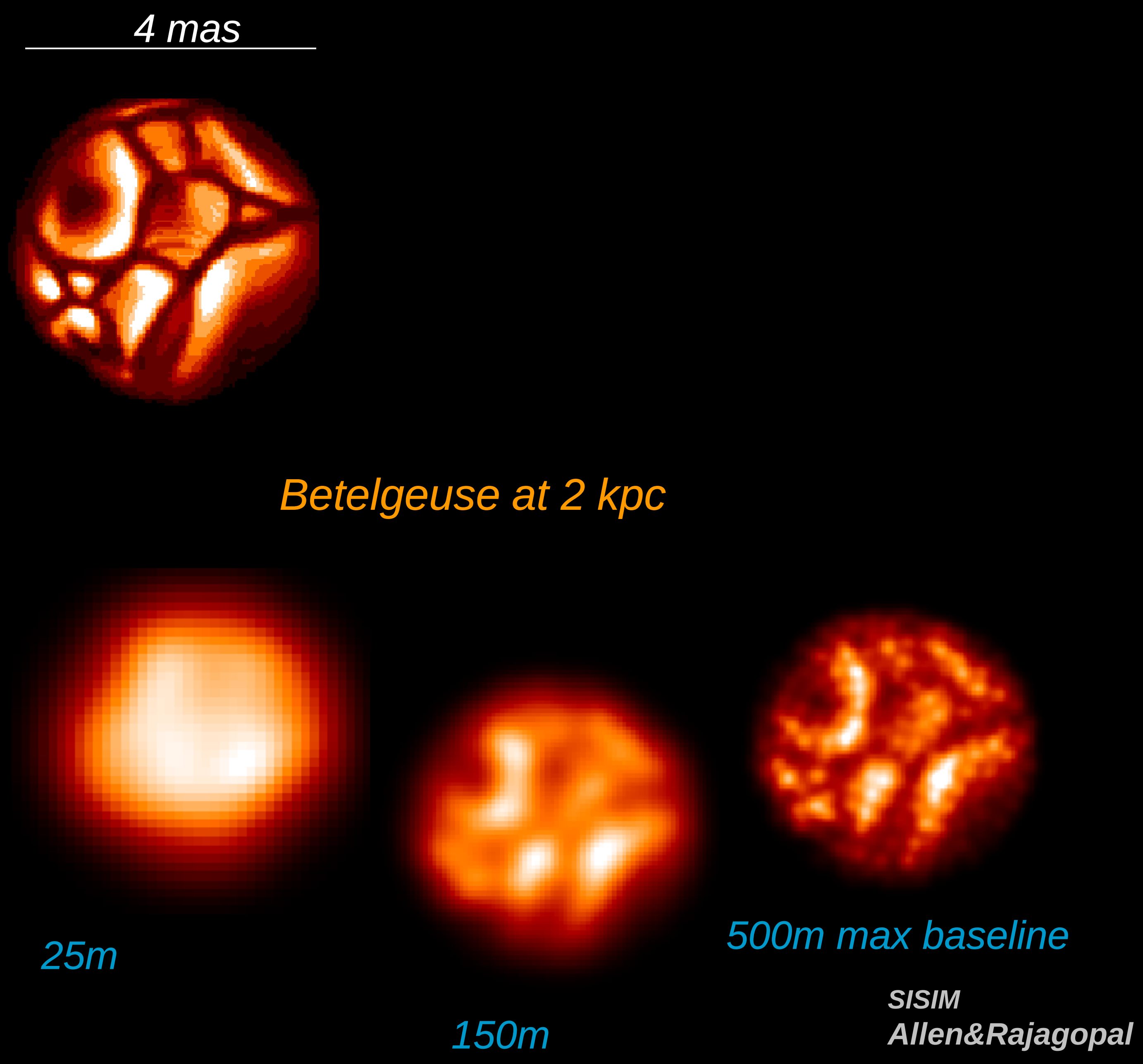
(Porter, Anderson, Woodward/Univ. MN)

2.5 m telescope view simulations



~HST

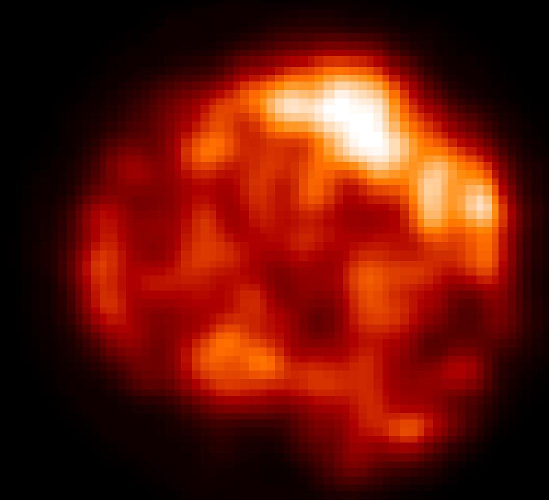



4 mas
Betelgeuse at 2 kpc
25m
150m
500m max baseline
SISIM
Allen&Rajagopal

Mira-type star at 2 kpc

4 mas

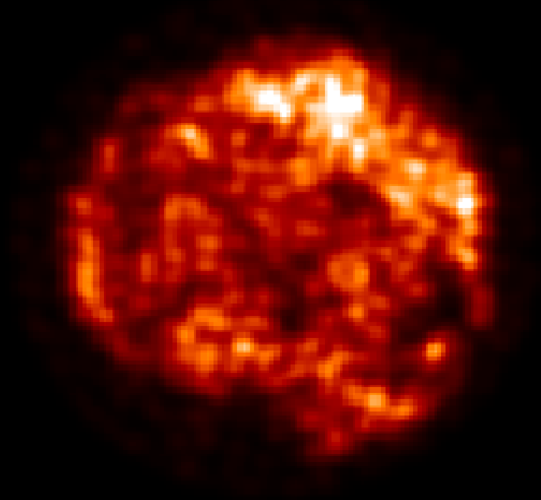
model



SI view at 250m baseline

Mira-type star at 2 kpc

model



SI view at 500m baseline

Required Capabilities for SI

- **wavelength coverage: 1200 – 6600 Å**
- **access to UV emission lines** from Lyα 1216 Å to Mg II 2800 Å
  - 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 temporal resolution spatially-resolved asteroseismology to resolve internal stellar structure
- angular resolution of 50 μas at 1200 Å (120 μas @2800 Å) to provide ~1000 pixels of resolution over the surface of nearby (4pc) dwarf stars, and more distant giant and supergiant stars.
- **angular resolution of 100 μas in far-UV** for observations of sizes & geometries of AGN engines, accretion processes in forming exo-solar systems, interacting binaries and black hole environs, and for dynamic imaging of evolving structures in supernova, planetary nebulae, AGN, etc.
- **energy resolution/spectroscopy** of R>100 (min) up to R=10000 (goal)
- Selectable “interferometric” and “light bucket/spectroscopic” modes
- a **long-term (~ 10 year) mission**, to enable study of stellar activity cycles:
  - individual telescopes/hub(s) can be refurbished or replaced

SI Requirements Flow Down

Science Goals

Solar/Stellar Magnetic Activity
-Understand the dynamo process responsible for magnetic activity
-Enable improved forecasting of solar/stellar magnetic activity on time scales of days to centuries
-Understand the impact of stellar magnetic activity on planetary climates and on the origin and continued existence of life

Magnetic Accretion Processes
-Understand accretion mechanisms in sources ranging from planet-forming systems to black holes
-Understand the dynamical flow of material and the role of accretion in evolution, structure, and transport of matter in complex interacting systems

AGN Structure
-Understand the close-in structure of AGN including jet forming regions, winds and transition regions between Broad & Narrow Line Emitting Regions.

Dynamic imaging of Universe at ultra-high resolution - understand the dynamical structure and physical processes in many currently unresolved sources, e.g. AGN, SN, PN, Interacting binaries, stellar winds and pulsations, forming-stars and disks regions, evolved stars.

Data Required

***Examples for solar/stellar targets*:**
-Empirical constraints to refine dynamo models (e.g. for a solar-type star at 4pc)
-Observations of spatial and temporal stellar surface patterns covering a broad range of magnetic activity levels
-Measurement of internal stellar structure and rotation

⇨ UV (1550 Å, 2800 Å) images with 1000 total resolution elements taken with modest integration times (~hours for dwarfs to days for giants)

⇨ Optical Asteroseismology with 30-100 total resolution elements over a stellar disk to measure non-radial resonant waves [integration times - minutes (dwarfs) to hours (giants)]

Examples for non-stellar targets:
-Measurement of sizes/geometries of BLRs, NLRs and opening angles in AGN; Spectral images of accretion processes in planet-forming regions, interacting binaries, BH environments;
-Dynamic imaging of jet-forming regions and evolving jets, e.g.in AGN, YSOs, PN, SN, interacting binaries

⇨ ~0.1 milliarcsecond imaging with spectral information (R>100) over the 1200 – 6600 A range to provide time-lapse images with dozens of resolution elements

****Mission lifetime of 5 yr (10 yr goal) needed to cover significant fraction of stellar activity cycles***

Measurements Req.

Angular Resolution :
0.1 mas @ 2000 Å
Spectral Range
1200 – 6600 Å
Field of View
~ 4 mas minimum
Flux Threshold at 1550 Å
5×10^{-14} ergs/cm^2/s
Observations
-several dozen solar-type stars observed repeatedly over mission lifetime (MLT)
-month-long seismology campaigns on select targets
-a sample of extragalactic & galactic sources (e.g. AGN SN, PN, stars, planet forming regions, binaries) observed several times during the MLT

Engineering Implications

Baselines from 100 to 1000m

~30 primary UV-quality mirrors of > 1 meter diameter

Fizeau Beam combination

Path Length Control to 3 nm

Aspect Control to 30 μas

Orientation +/-20 deg to orthogonal to Sun

Key Technologies

-precision metrology and formation-flying

-wavefront sensing and closed-loop control of many-element optical systems

-deployment/initial positioning of elements in large arrays

-metrology/autonomous nm-level control of many-element formations over kms

-variable, non-condensing, continuous μ-Newton thrusters

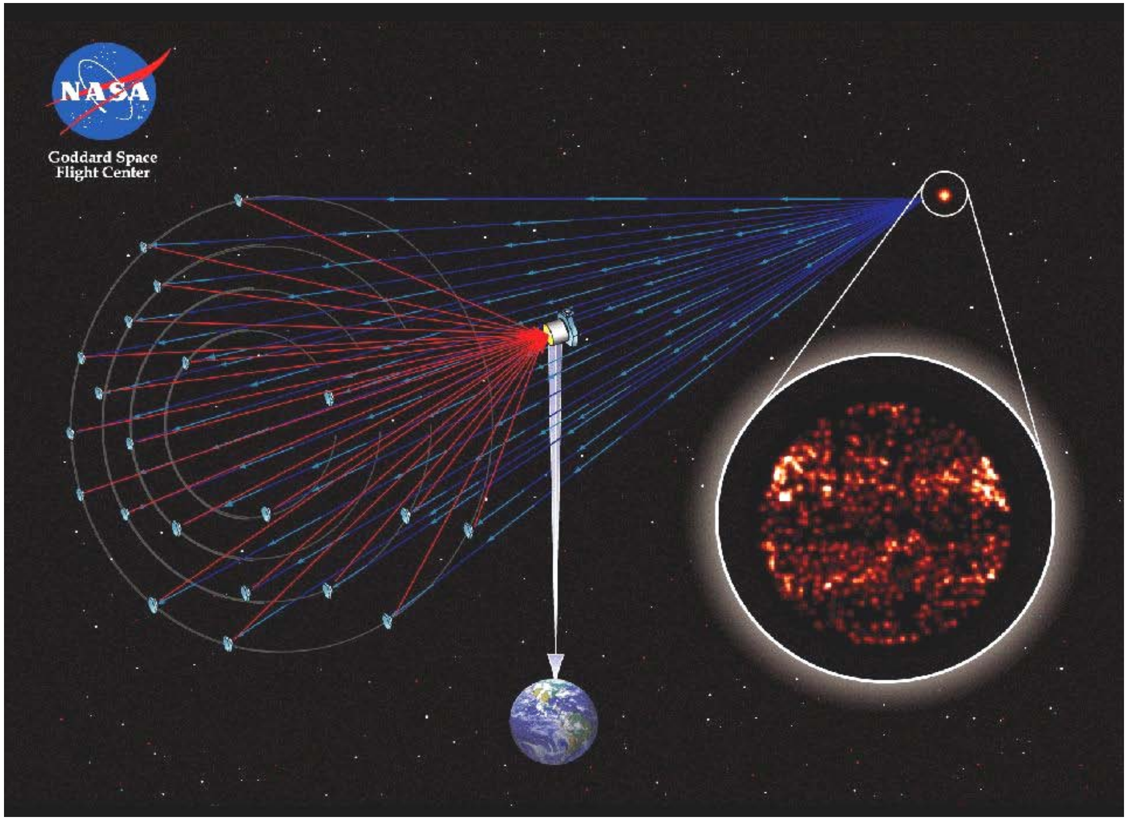
-light-weight UV quality spherical mirrors with km-long radii of curvature

-larger format energy resolving detectors with finer energy resolution (R=100) or a Spatial Frequency Remapper beam combiner to enable spectral dispersion of each beam

-methodologies for ground-based integration and test of distributed s/c systems

-mass-production of "mirrorsat" spacecraft

SI Concept from Vision Mission (VM) Study

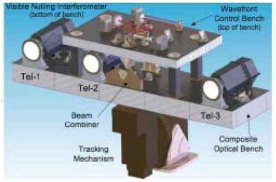


- a 0.5 km diameter space-based UV-optical Fizeau Interferometer
- located near Sun-earth L2 to enable precision formation flying
- 30 primary mirror elements focusing on beam-combining hub
- large advantages to flying more than 1 hub:
  - critical-path redundancy & major observing efficiency improvements

Feasibility of Interferometry from Space

- SI is part of a natural evolution from current ground-based interferometers and testbeds to a space-based system (see next page)
- Feasibility of interferometry demonstrated by large variety of successful ground-based interferometers (e.g., CHARA, COAST, NPOI, and VLTI)
  - Their performance, and that of space-based interferometers, can be improved simply by increasing # of elements, as has been done for radio facilities
- Space provide better environment
  - Not looking through an atmosphere, which on the ground limits spatial and temporal coherence (aperture size and integration time) of incoming wavefront
  - No need for large and complicated delay lines for off-axis obs.
  - Wavelengths not available from ground can be accessed
- A simple imaging interferometer, like SI, is a logical first "large baseline, space-based" interferometer
  - it is easier than an astrometric mission like SIM, since its light-path delay tolerance is ~2 orders of mag less than SIM's $\lambda/1000$ level
  - It is easier than TPF-I-like missions aimed at planet detection via nulling the central star and requiring a fringe contrast ~0.99999 and having error requirements ~10000x more severe than SI with its 0.9 fringe contrast requirement
- A small-baseline space interferometer with just a few primary mirrors (e.g., SI-Pathfinder, Fourier-Kelvin Stellar Interferometer (FKSI), or Pegase) would be an ideal bridge from the ground-based to large baseline space-based interferometers

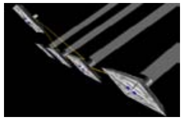
Notional Path for Development of Space Interferometry



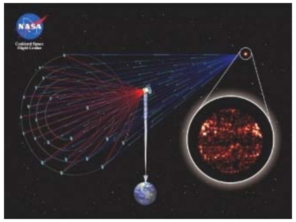
Balloon-Based Missions:
BENI or BETTII

Space Tech. Demos:
ST-9 or Proba-3

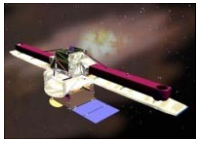
Planet Finders:
SIM & TPF



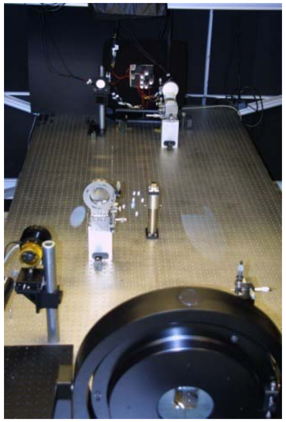
Large Strategic ("Vision") Imaging Interferometry Space Missions



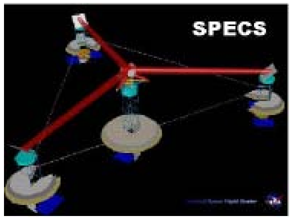
Stellar Imager
UV-Opt./Magnetic Activity



Smaller Space Interferometers
(e.g., SI-Pathfinder, FKSI and/or Pegase)



Ground-Based Testbeds
Wavefront Sensing/Control:
FIT, STAR9, FKSIT
Formation Flying:
SIFFT, FFTB, FCT
Metrology: SAO-TFG

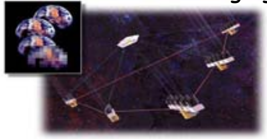


SPIRIT/SPECS
IR "Deep Fields"

Black Hole Imager
X-ray/BH Event Horizons

Life Finder
Searching for Signs of Life

Planet Imager
Terrestrial-Planet Imaging



Ground-based interferometers
(Keck, VLTI, LBT, ISI, CHARA, COAST, GI2T, NPOI, MRO)
Giant star imaging, Binary stars

2005 — 2010 — 2015 — 2020 — 2025 +

Enabling Stellar Imager: Technology Investments are Essential

- **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 control to 10's of micro-arcsec
  - positioning mirror surfaces to 2 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 control
  - multiple modes to cover wide dynamic range
- **wavefront sensing and real-time, autonomous analysis & control**
  - use the science data stream to control nm-level placement of mirrors
- **methodologies for ground-based validation of distributed systems**
- additional challenges (perceived as easier than the above)
  - mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test
  - long mission lifetime requirement
  - light-weight UV quality mirrors with km-long radii of curvature (perhaps deformable UV quality flats)

Addressing the Technical Challenges

- The technology challenges identified on the previous slide have all been addressed prior to and during the SI Vision Mission (VM) study:
  - in both IMDC and ISAL sessions dedicated to SI development over the period 2001-2005
  - and in other Integrated Design Center studies run as joint efforts with other interferometric design efforts (e.g., a joint study with MAXIM optimizing techniques for aspect control of spacecraft to the 10's of micro-arcsec level).
- Credible and feasible approaches to the successful development of all these technologies were derived during the course of those studies and are documented in the SI VM Final Report.
- A notional "Path for the Development of Space Interferometry" has been developed (see earlier slide)
- In addition, there are a number of ground-based testbeds which are aggressively pursuing the development of these technologies, including the development and assessment of:
  - precision formation flying (PFF) algorithms (SIFFT/SPHERES, FFTB)
  - 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 (FIT)
  - high-precision metrology (SAO & JPL Testbeds)

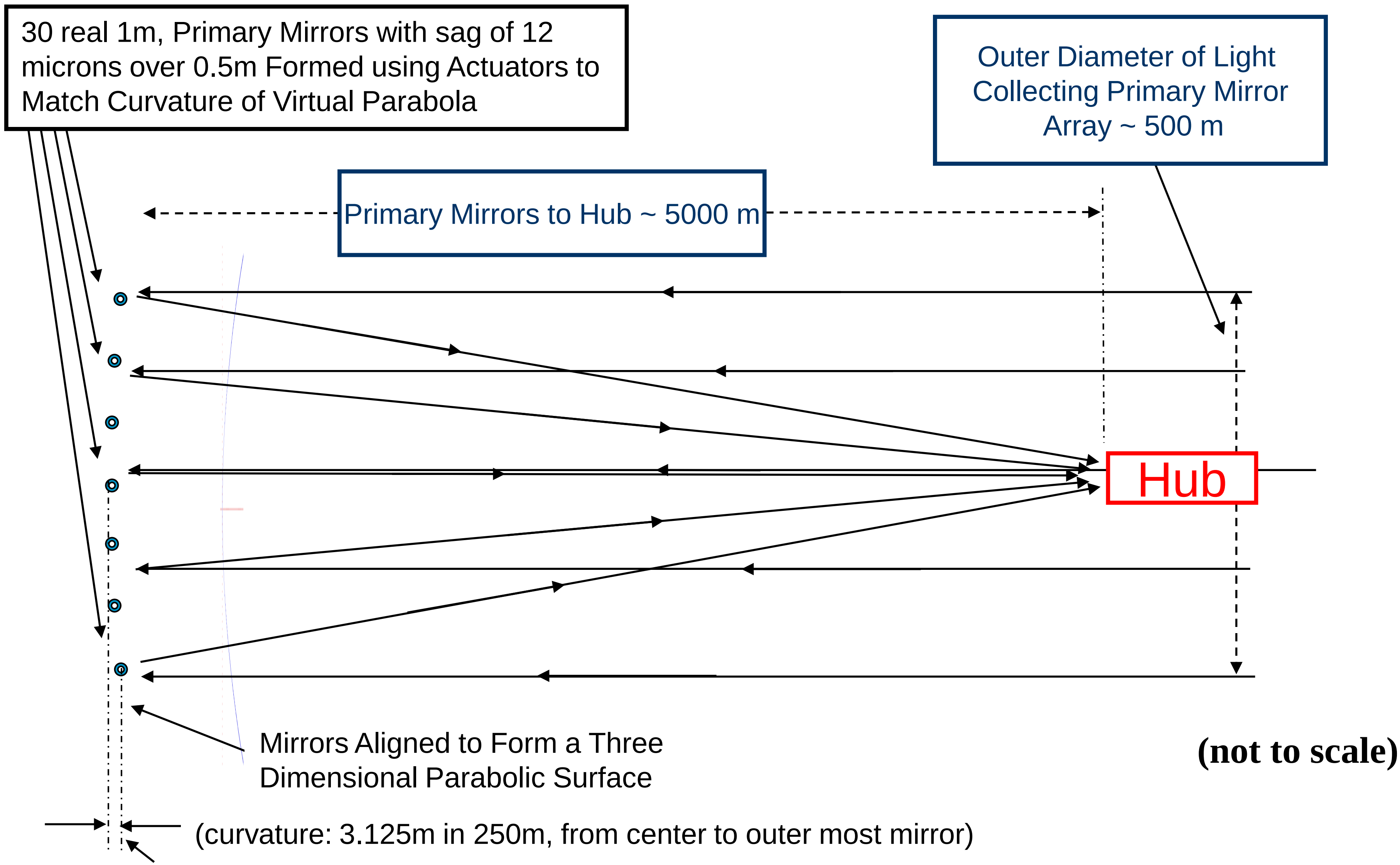
“Stellar Imager (SI) Pathfinder” Mission

A small UV/Optical Space Interferometer

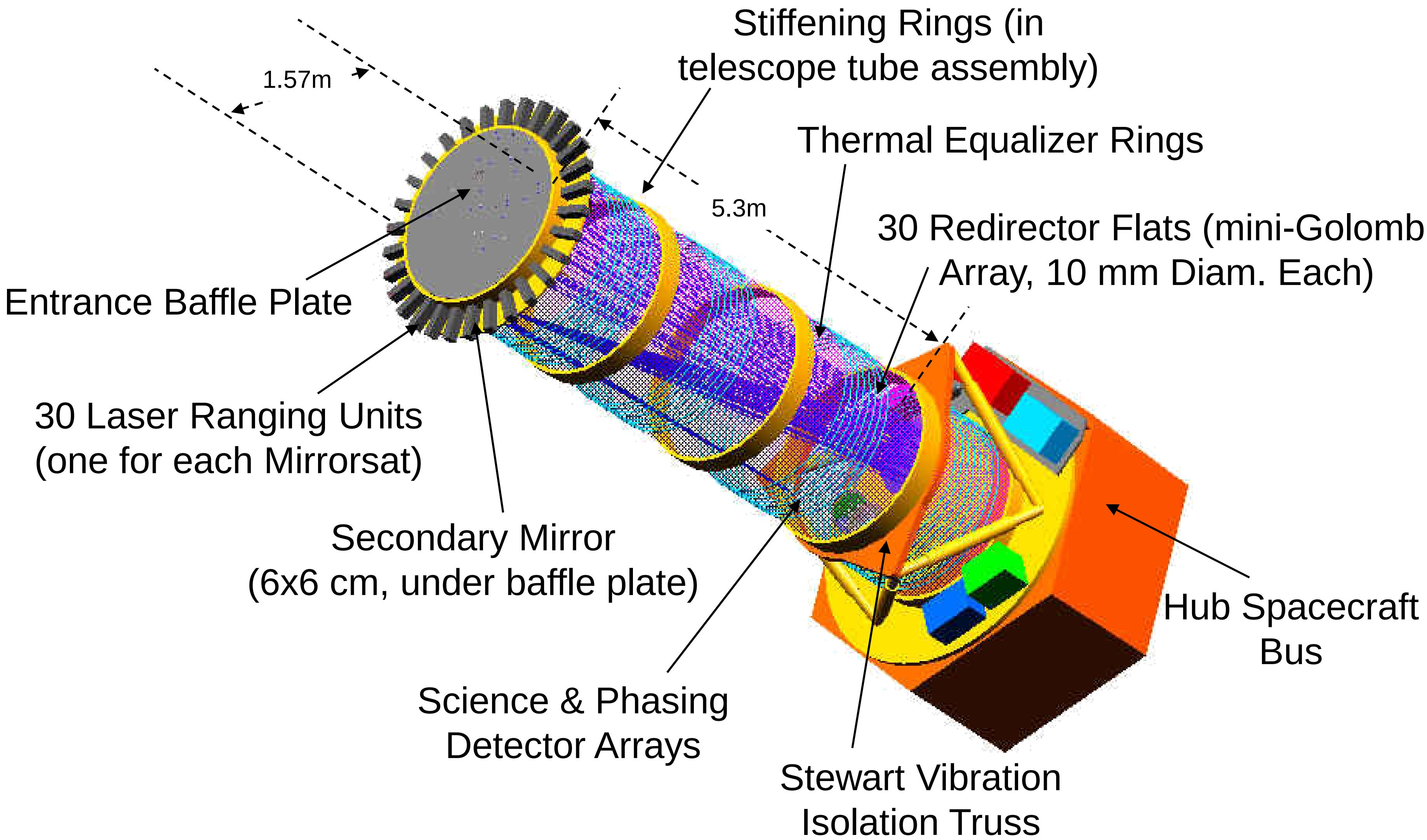
- to be launched within a decade
- with a modest # (3-5) of free-flying or boom-mounted spacecraft
- with modest baselines (~ 50 m)
- performing beam combination with UV light and demonstrating true imaging interferometry
- will enable significant new science by exceeding HST’s resolution by ~ 20x

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

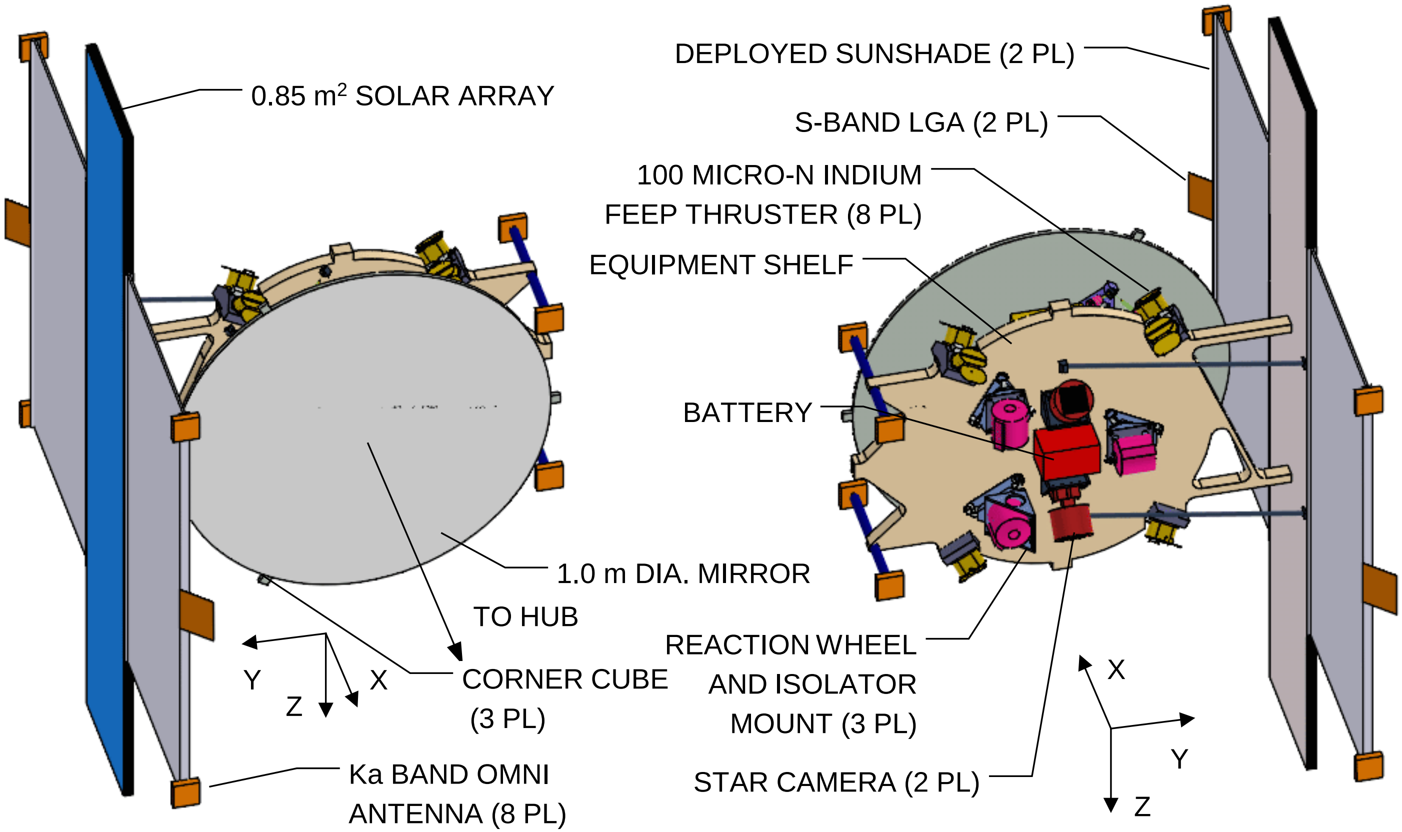
SI Cross-Sectional Schematic



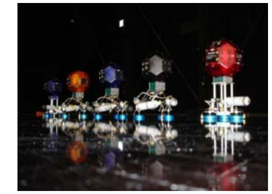
Principal Elements of SI Hub

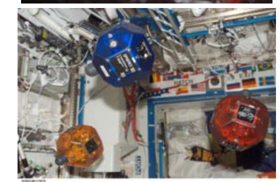


Mirrorsats: BATC (Lightweight) Option

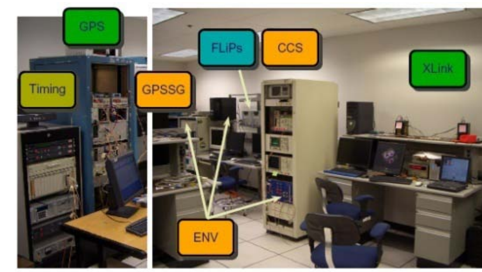


GSFC/SI Technology Development Programs

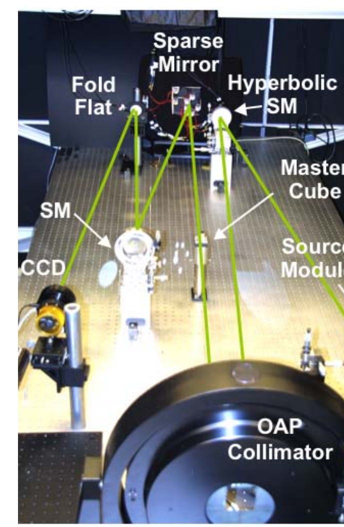




- **GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT; Carpenter, Lyon, Stahl, Miller, et al.)**
  - Develop cm-level formation flying algorithms on lab hardware, including Formation Deployment/Maintenance, Reconfiguration, Imaging Maneuvers
  - Uses MIT SPHERES on the MSFC Flat Floor and on ISS
  - Have demonstrated formation control of 3 floating SPHERES and reconfiguration by rotating/expanding formation



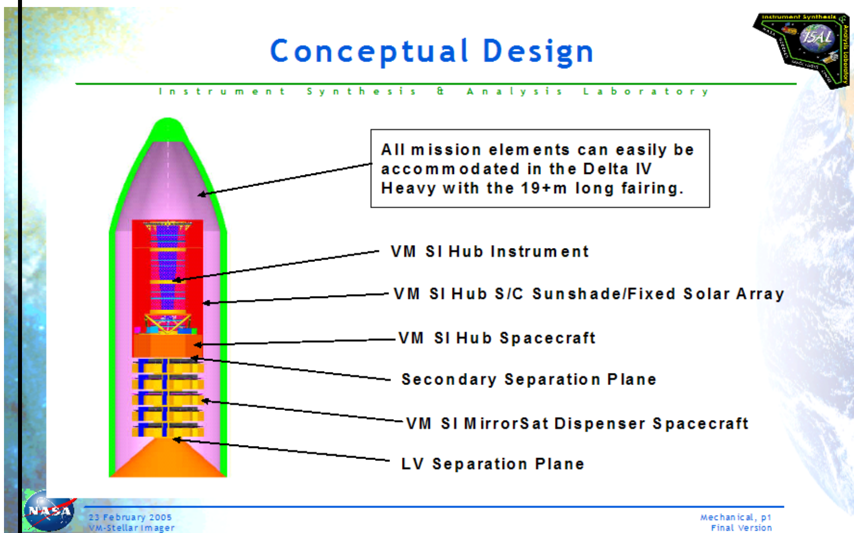
- **GSFC Formation Flying Testbed (FFTB; J. Leitner, E. Stoneking, J. Mitchell, R. Luquette)**
  - Software simulation facility
  - Used to develop & demo deployment of array s/c and multi-stage acquisition of target light from individual mirrors by beam combiner
  - Stoneking simulated all stages of formation acquisition for full-up SI



- **Fizeau Interferometer Testbed (FIT; K. Carpenter, R. Lyon, A. Liu, D. Mozurkewich, P. Petrone, P. Dogoda)**
  - Develop & demo closed-loop, nm-level optical control of a many-element sparse array, ***using wavefront sensing of the science data stream***
  - Develop/assess image synthesis algorithms
  - Develop nulling techniques for Fizeau Interferometers for planet detection/imaging

The Ultimate Goal: develop Staged-Control Methodologies covering over 12 orders of magnitude, from nm to km scales

There are several viable launch options for designs with 1-meter array elements (the baseline VM design)

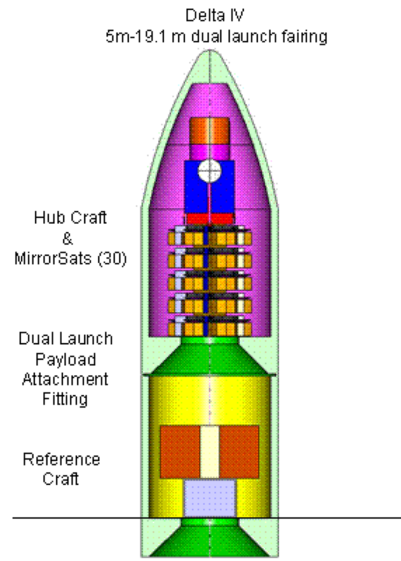


Delta IV Heavy / 19+m fairing:

- 1 hub
- no reference craft
- 30 1-m primary array elements

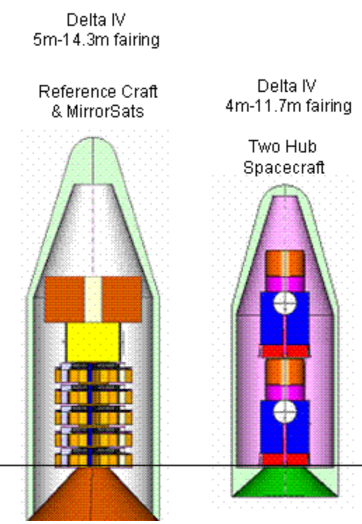
Delta IV/5x19.1m:

- 1 hub
- 1 reference craft
- 30 1-m primaries



Two Delta IVs:

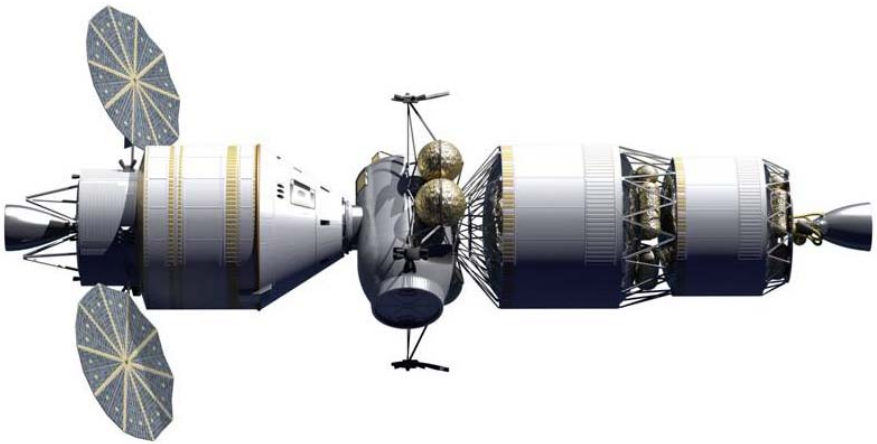
- 2 hubs
- 1 reference craft
- 30 1-m primaries



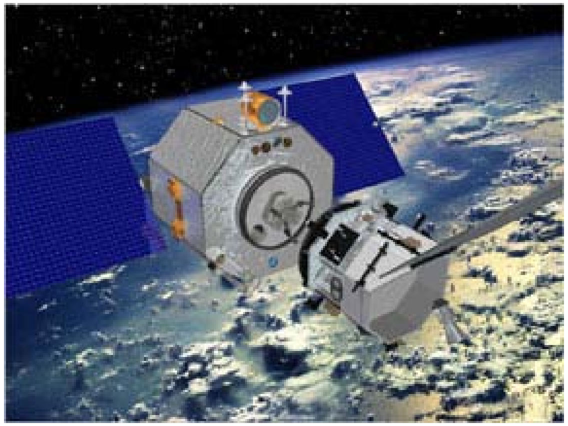
These options accommodate launch of a system with 1-m diameter primary array elements. If larger array elements are deemed desirable, then the Ares V or a similar large-fairing vehicle (e.g. Atlas V HLV) rocket can provide a robust option for a single-launch deployment of a system with larger mirrors.

Value of In-Situ Servicing to SI

- SI can benefit significantly if elements can be serviced during extended operations (re-fueled, fixed, replaced), perhaps by humans in the Orion vehicle, or by robotic means…



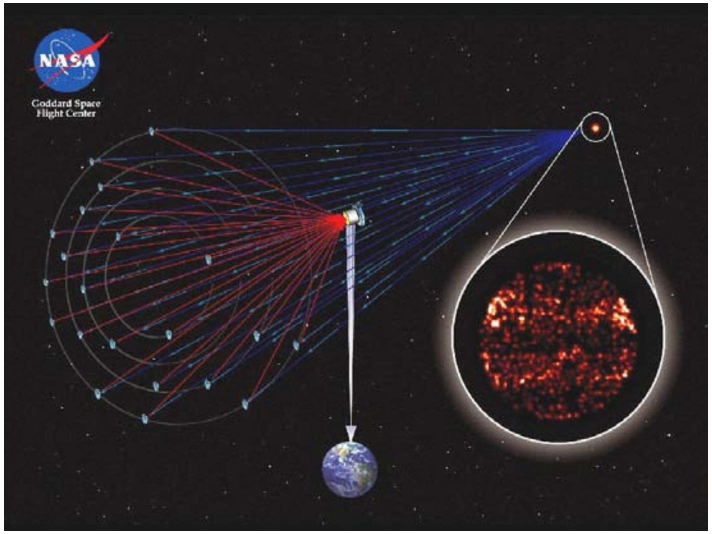
LSAM L1 Stack
(Orion/CEV mated to a crew module)
http://www.futureinspaceoperations.com/



Orbital Express has demonstrated feasibility of autonomous (robotic) on-orbit refueling and reconfiguration:
http://www.darpa.mil/orbitalexpress/

Stellar Imager (SI): Summary

- UV-Optical Interferometer to provide 0.1 mas spectral imaging of
  - magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, transport processes on many scales in Universe
- A “Flagship” (Vision) mission in the NASA 2005 Heliophysics Roadmap
- A candidate for the UVOI in the 2006 Astronomy & Physics Div. Science Plan
- Mission Concept
  - 30 “mirrorsats” formation-flying with beam combining hub
  - Launch ~ 2024, to Sun-Earth L_2
  - baselines ~ 100 - 1000 m
  - Mission duration: ~10 years



Prime Science Goals

Understand the Role of Magnetism in the Universe and thereby *revolutionize our understanding* of:

Solar/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

The close-in structure of Active Galactic Nuclei (AGN) and Quasars, and their winds

Exo-Solar Planet Transits and Disks

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

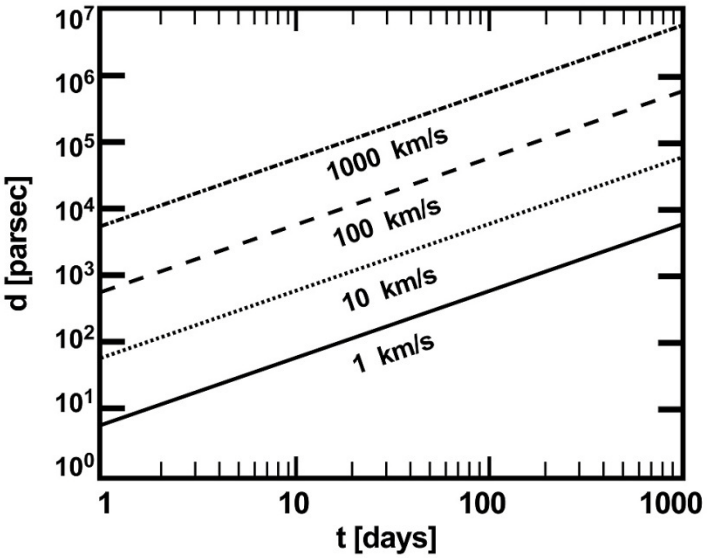
Additional Information

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
•-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: 70º < b < 110º	Entire sky in 180 d
Hub Dry Mass	1455 kg	Possibly 2 copies
Mirrorsat Dry Mass	65 kg (BATC) - 120 kg (IMDC)	For each of up to 30
Ref. Platform Mass	200 kg	
Total Propellant Mass	750 kg	For operational phase
Angular Resolution	50 mas – 208 mas (@1200–5000Å)	Scales linearly ~ •/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 x 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 mm-nm level	
Phase Corrections	to •/10 Optical Path Difference	
Aspect Control/Correct.	3 mas for up to 1000 sec	Line of sight maintenance

SI will bring the study of the dynamical evolution of many astrophysical objects into reach for the first time

Hours to weeks between successive images will detect dramatic changes in many objects – for example:

- 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 AGN
- and many other variable and evolving sources



Mission Concept Development Team

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

Arizona State University	Catholic University of America
Ball Aerospace & Technologies Corp.	Lockheed Martin Adv. Tech. Center
Marshall Space Flight Center	Massachusetts Inst. of Technology
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&SanAn.
European Space Agency	College de France
Astrophysical Institute Potsdam	University of Aarhus

- Institutional and topical leads from these institutions include:
  - K. Carpenter, C. Schrijver, M. Karovska, A. Brown, A. Conti, K. Hartman, S. Kilston, J. Leitner, D. Lakins, A. Lo, R. Lyon, J. Marzouk, D. Miller, D. Mozurkewich, J. Phillips, P. Stahl, F. Walter

- Additional science and technical collaborators from these institutions include:
  - S. Baliunas, C. Bowers, S. Cranmer, M. Cuntz, W. Danchi, A. Dupree, M. Elvis, N. Evans, C. Grady, T. Gull, G. Harper, L. Hartman, R. Kimble, S. Korzennik, S. Kraemer, M. Kuchner, S. Leitch, M. Lieber, C. Lillie, J. Linsky, M. Marengo, R. Moe, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, A. Roberge, D. Sasselov, S. Saar, E. Schlegel, J. Schou, P. Scherrer, W. Soon, G. Sonneborn, E. Stoneking, R. Windhorst, B. Woodgate. R. Woodruff

- International Partners include:
  - J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, A. Labeyrie