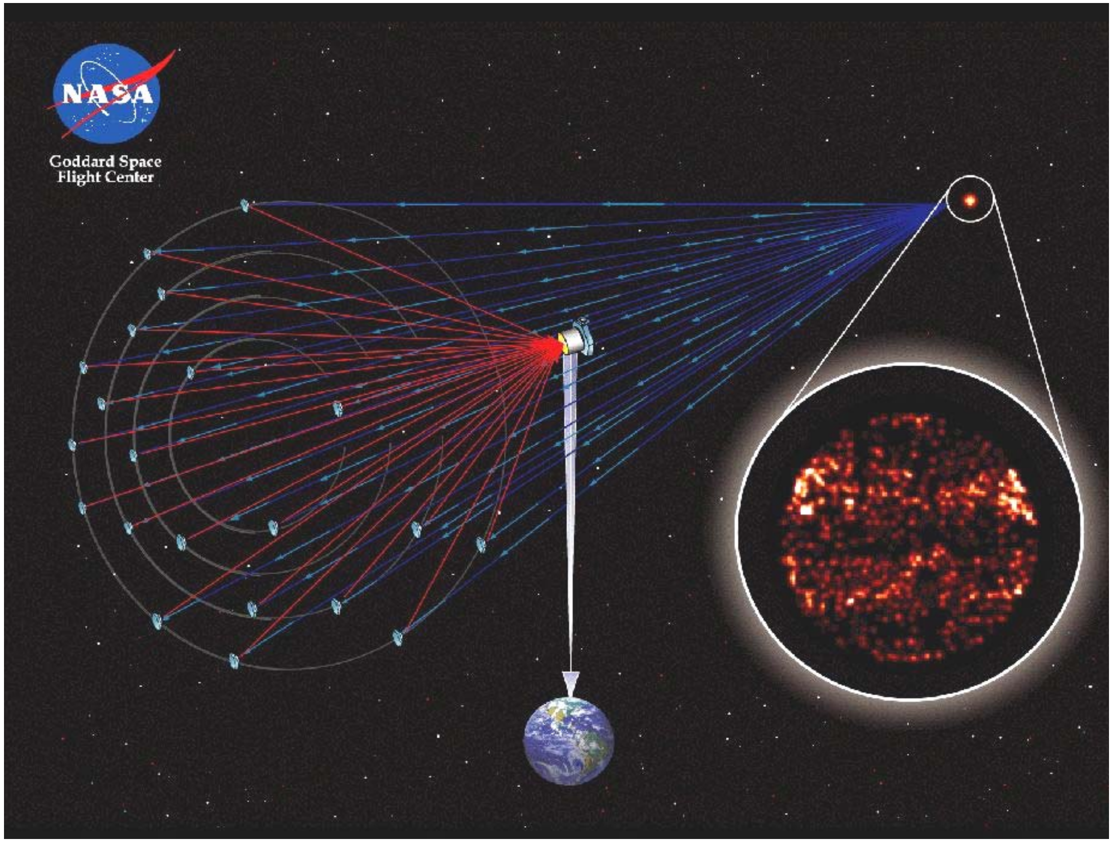
The Stellar Imager (*SI*) Project:
Resolving Stellar Surfaces, Interiors, and Magnetic Activity

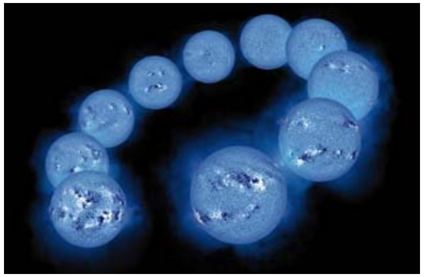


K. G. Carpenter (NASA/GSFC), C. J. Schrijver (LMATC), M. Karovska (SAO)
and the SI Mission Concept Development Team

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

Presented at the 1st NUVA Conference: Space Astronomy: the UV Window to the Universe
28 May – 1 June, 2007, in El Escorial, Spain

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**

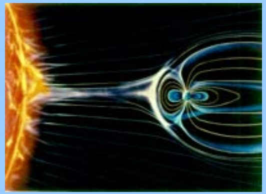
Science goals of the Stellar Imager

- 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.

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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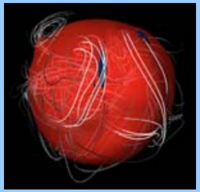

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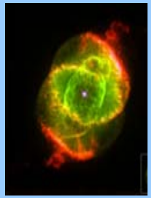
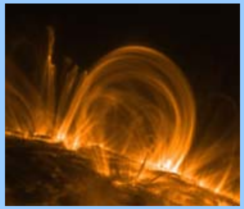
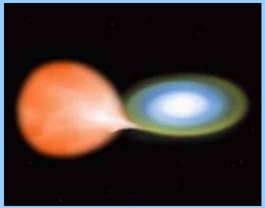


The cradle of life **Stellar activity & planets, life** **Dying giants**

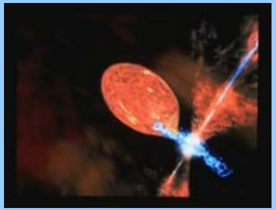
How does the dynamo evolve?



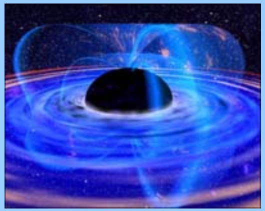
The Sun



Interacting binary



Accretion, jets, outflows



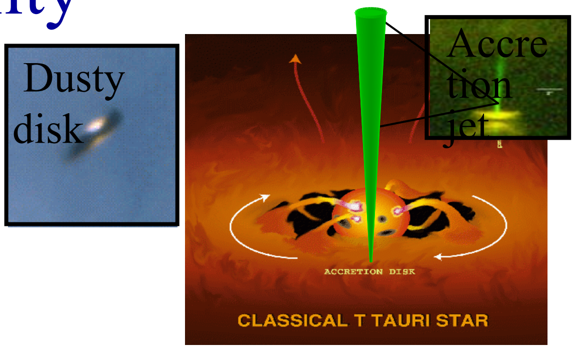
Accreting AGN

Can we generalize stellar dynamo properties?

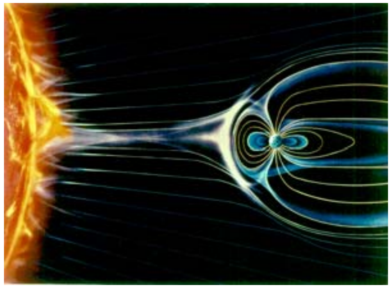
Science Driver: Stellar Activity is Key to Understanding Life in the Universe and Earth's habitability

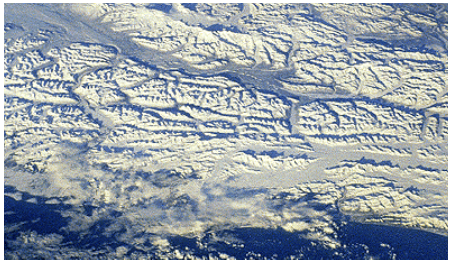
The stellar magnetic field

- 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

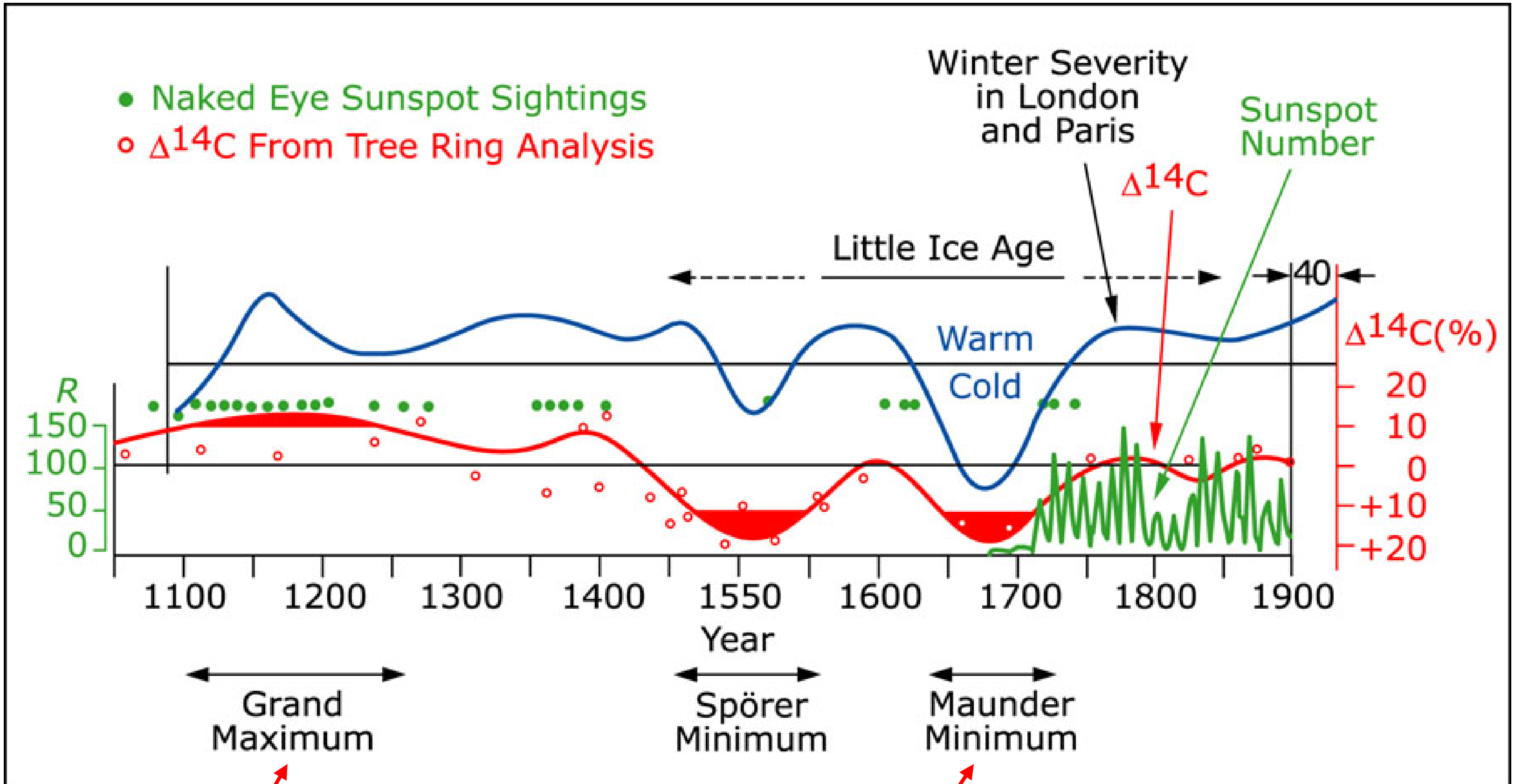


Star/Planet Formation


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

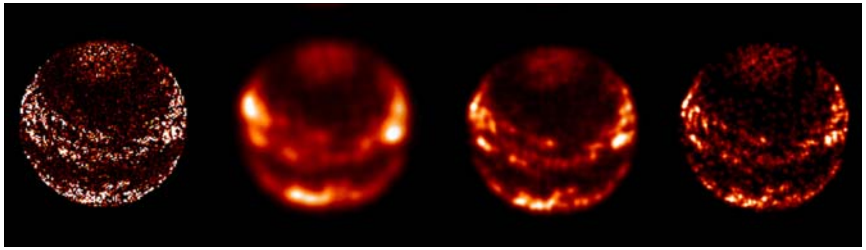
Interacting Binary Systems
resolve mass-exchange, dynamical evolution/accretion, study dynamos

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

What Will Stellar Imager See?

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

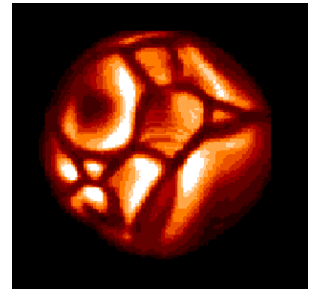
Model **SIsim images**



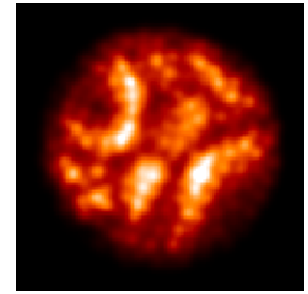
Baseline: 125m **250m** **500 m**

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

Model

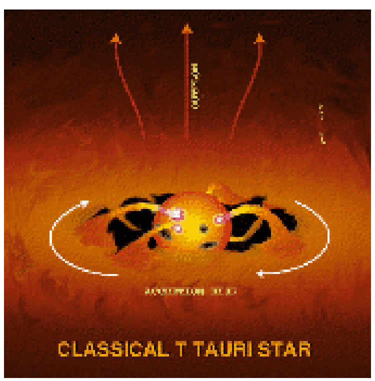


***SIsim* image (2mas dia)**

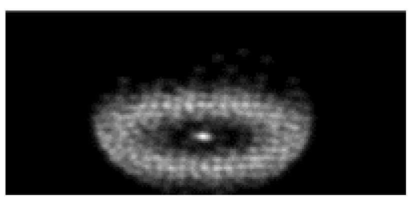


Baseline: 500 m

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



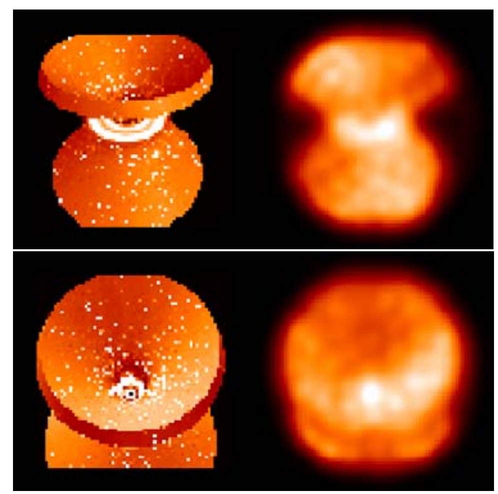
0.1 mas



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

Baseline: 500 m

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



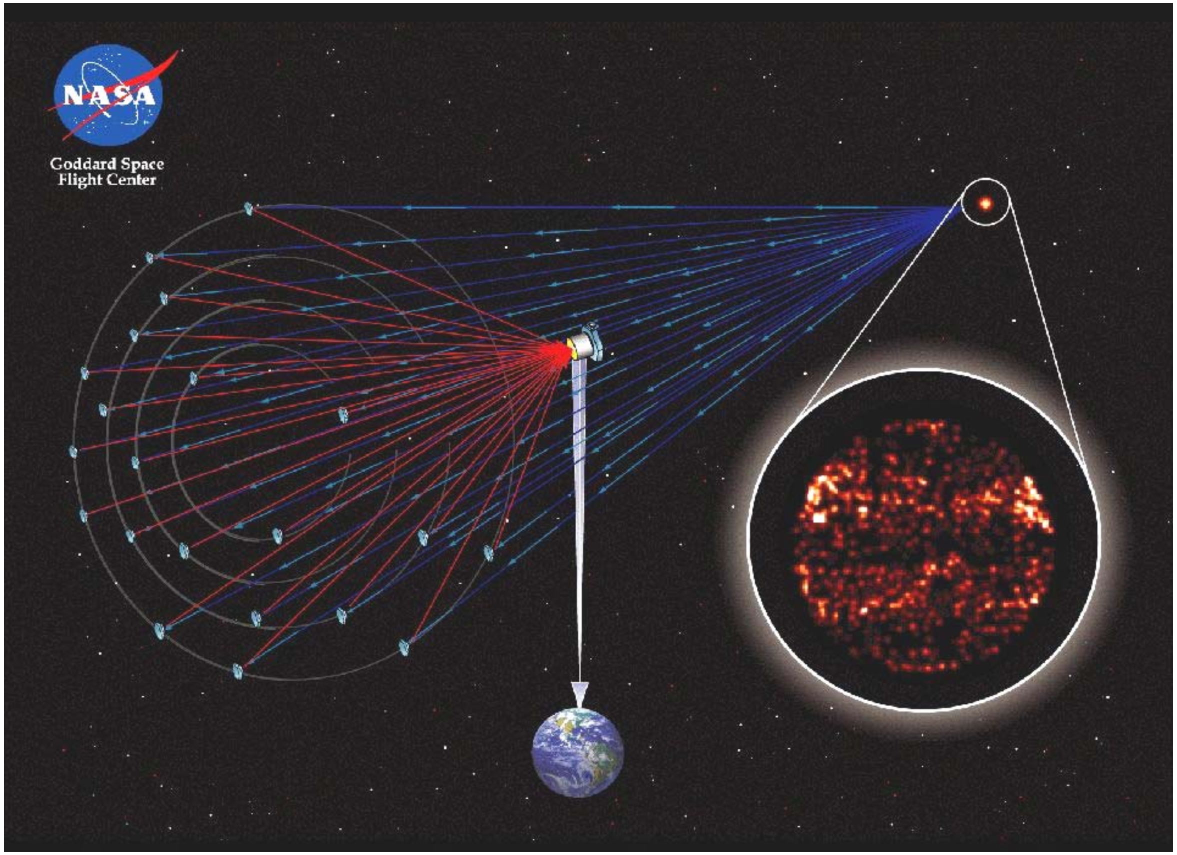
0.1 mas

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

Required Capabilities for SI

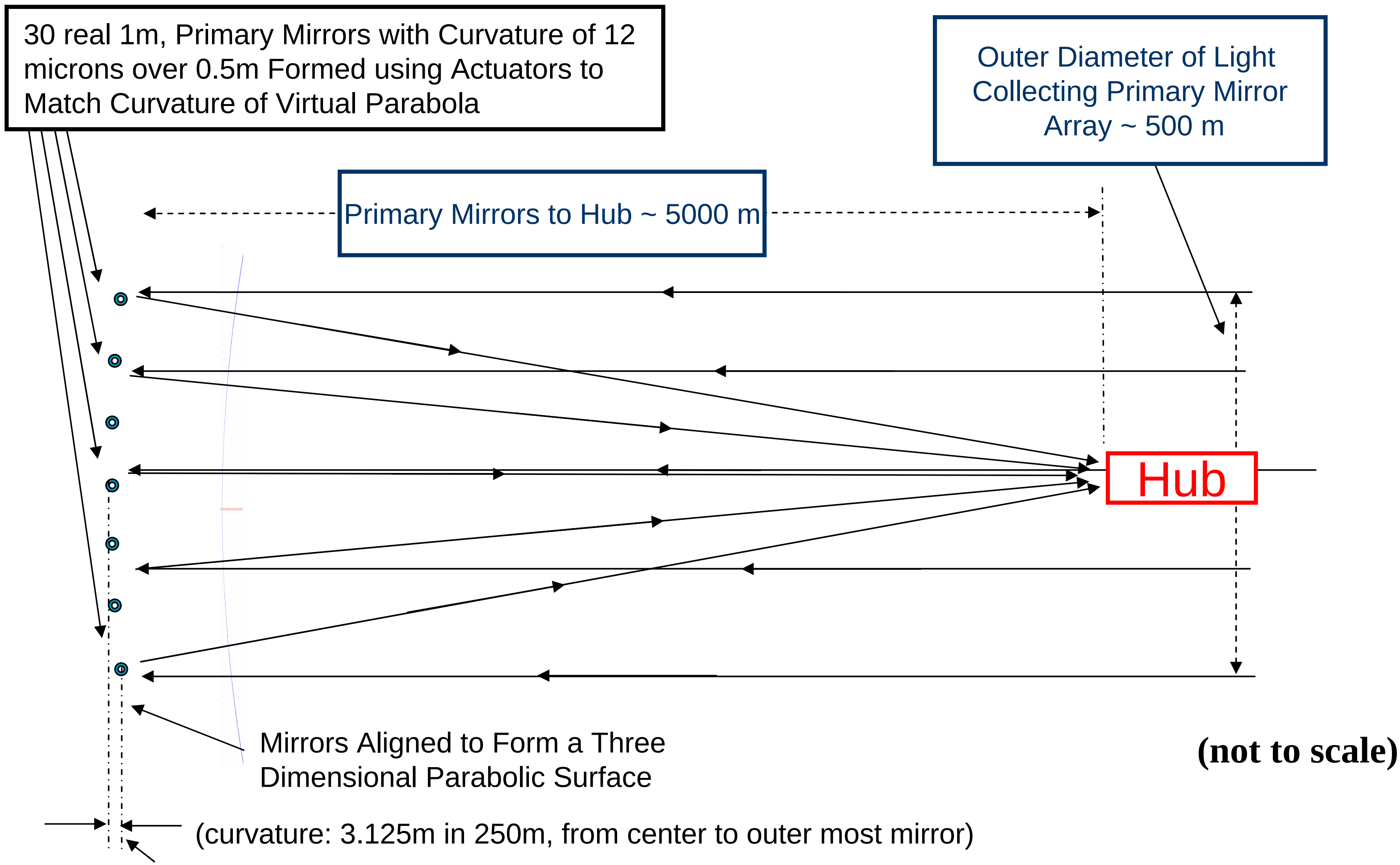
- Wavelength coverage: 1200 – 5000 Å
- access to UV emission lines from Ly-alpha 1216 Å to Mg II 2800 Å for stellar surface imaging
  - Important diagnostics of most abundant elements
  - much higher contrast between magnetic structures and background
  - smaller baselines (UV save 2-4x vs. optical, 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 temporal resolution spatially-resolved asteroseismology to resolve internal structure
- angular resolution of 50 micro-arcsec at 1200 Å (120 μas @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



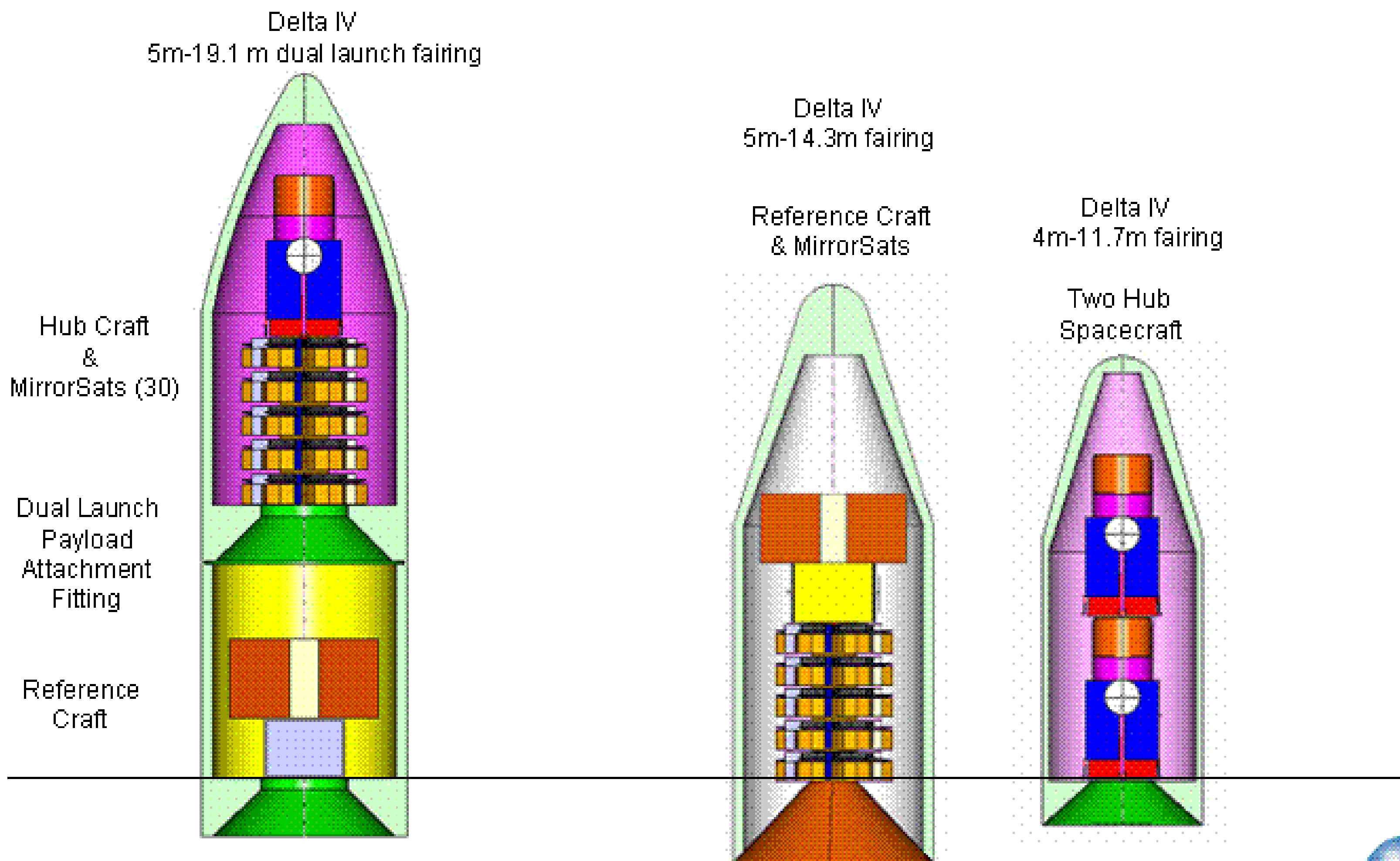
- a 0.5 km diameter space-based UV-optical Fizeau Interferometer
- located near Sun-earth L2 to enable precision formation flying
- 20-30 primary mirror elements focusing on beam-combining hub
- large advantages to flying more than 1 hub:
  - critical-path redundancy & major observing efficiency improvements

SI Cross-Sectional Schematic



Launch Configuration
Dual vs. Single Launch

Integrated Mission Design Center



4-7 Oct 2004
SI-VM

Sensitive Information
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Mechanical, p3
Final Version

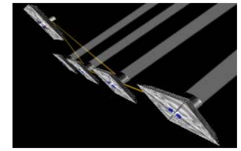
Top Technological Challenges and Enabling Technologies

- **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 → 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** (2 nm over multi-km baselines)
  - 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 (perhaps using deformable UV quality flats)
  - larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)

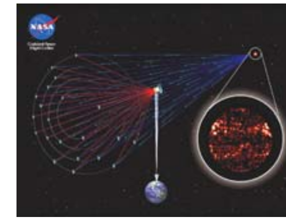
Notional Path for Development of Space Interferometry

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

Planet Finders:
SIM & TPF



Strategic ("Vision") Imaging Interferometry Space Missions



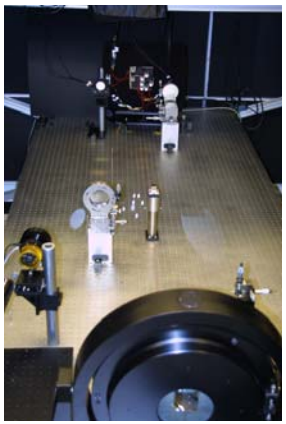
Stellar Imager
UV-Opt./Magnetic Activity

SPECS
IR "Deep Fields"

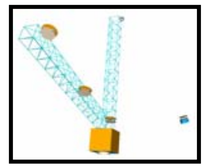
Black Hole Imager
X-ray/BH Event Horizons

Life Finder
Searching for Signs of Life

Planet Imager
Terrestrial-Planet Imaging



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



Smaller Space Interferometers

SI Pathfinder
UV/Optical
FKSI and Pegase
small IR
SPIRIT
IR (boom)
MAXIM-PF
X-Ray

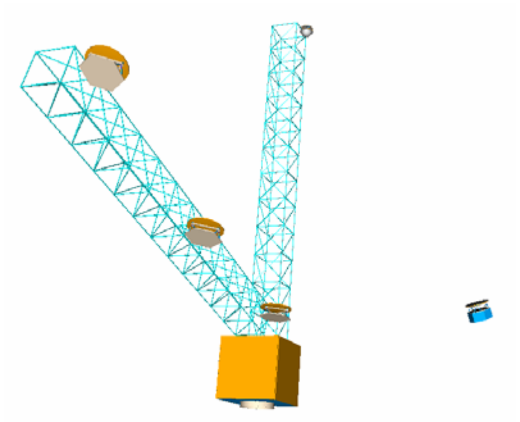
Ground-based interferometry
(Keck, VLTI, LBT, ISI, CHARA, COAST, GI2T, NPOI, MRO)
Giant star imaging, Binary stars

2005 — 2010 — 2015 — 2020 — 2025 +

"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

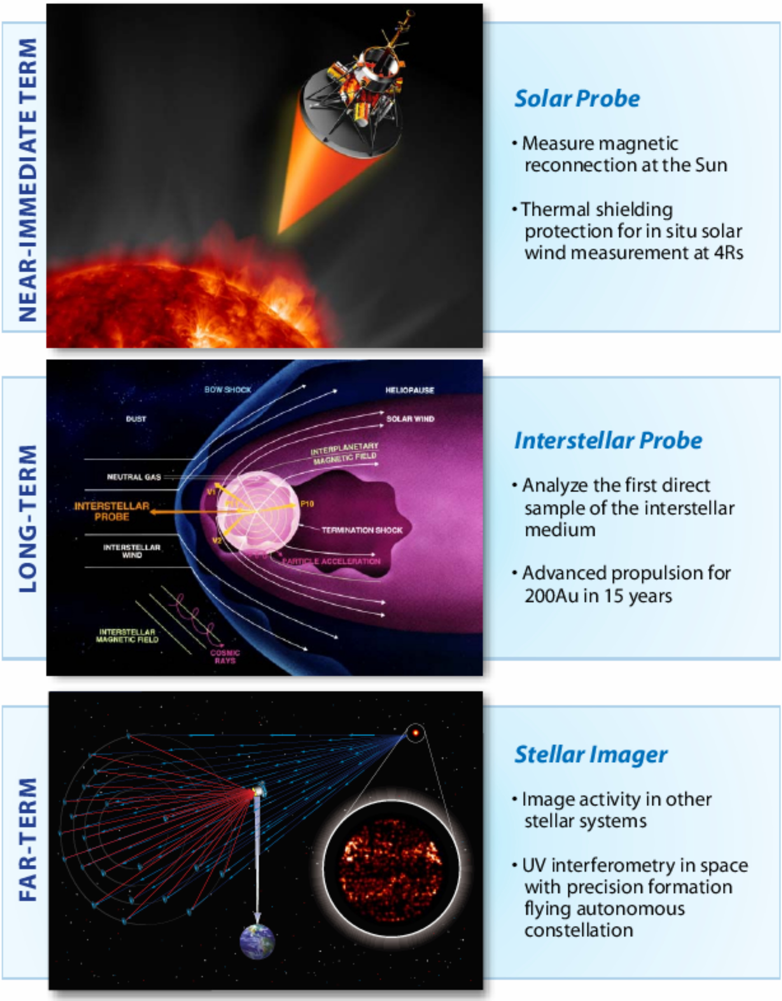


- Such a mission with a small # of spacecraft
  - requires frequent reconfigurations and limits observations to targets whose variability does not preclude long integrations
  - *but tests most of the technologies needed for the full-size SI and other interferometry missions*

SI Status

- SI in NASA SEC/SSSC/Heliospheric Division Roadmap since 2000
- SI selected in 2003 for concept development as NASA “Vision Mission”
- Partnerships established w/ LMATC, SAO, BATC, NGST, JPL, CU to develop concept
- The Fizeau Interferometry Testbed (FIT) is developing nm-level closed-loop optical control of a multi-element array (GSFC)
- The Synthetic Imaging Formation-Flying Testbed (SIFFT) is developing cm-level formation-flying of an array of spacecraft (GSFC/MIT/MSFC)
- GSFC Integrated Mission Design Center and Instrument Synthesis & Analysis Lab studies produced system design & technology development roadmap
- **In 2005 NASA Strategic Roadmaps, SI is included as**
  - **A “Flagship” (Landmark Discovery) mission in the SSSC (Heliospheric) Roadmap**
  - **A candidate “Pathways to Life Observatory” in the EUD Roadmap**

SSSC (Heliospheric Sciences) Landmark Discovery Missions



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
  Astrophysical Institute Potsdam

  Kiepenheuer Institute
  University of Aarhus

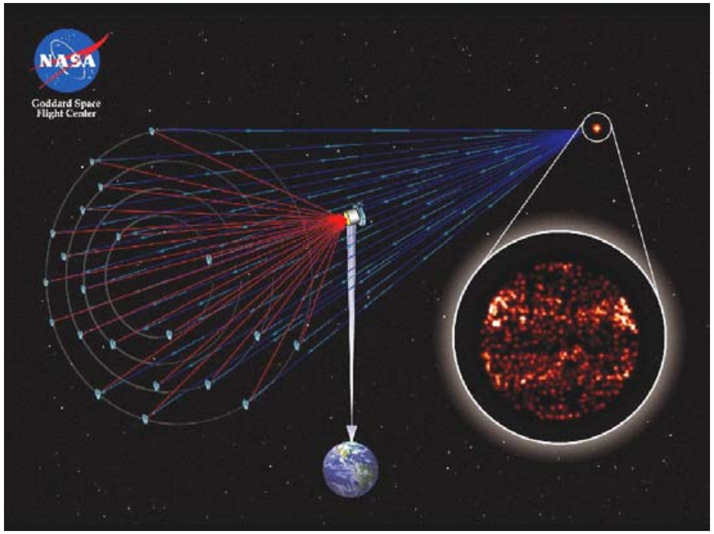
- Institutional and topical leads from these institutions include:
  - K. Carpenter, C. Schrijver, R. Allen, A. Brown, D. Chenette, D. Mozurkewich, K. Hartman, M. Karovska, S. Kilston, J. Leitner, A. Liu, R. Lyon, J. Marzouk R. Moe, N. Murphy, J. Phillips, F. Walter

- Additional science and technical collaborators from these institutions 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. Linsky, M. Marengo, L. Mazzuca, J. Morse, L. Mundy, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, D. Sasselov, E. Schlegel, J. Schou, P. Scherrer, M. Shao, W. Soon, G. Sonneborn, R. Stencel, B. Woodgate

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

Stellar Imager (SI): UV/Optical Space Interferometry

- 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 SSSC Roadmap and a candidate “Pathways to Life Observatory” in the NASA 2005 EUD Roadmap
- Mission Concept
  - 20-30 “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

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 of Active Galactic Nuclei, Quasars, Supernovae, Interacting Binary Stars, Forming Stars/Disks

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

Extra slides

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	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 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 maintenance

Simulated SI Images (1550 Å) for Various #Mirrors/Rotations

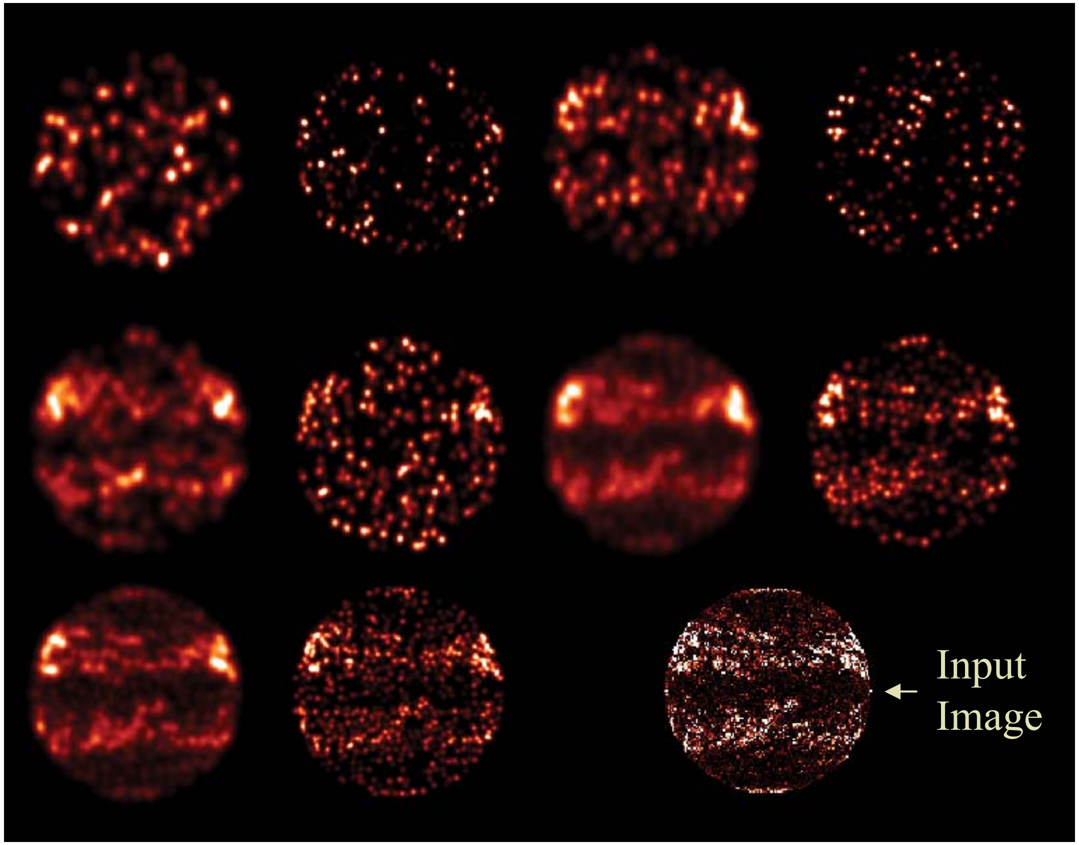
“Snapshots” (no rotations) (24 array rotations)

elements (layout)

6 (Y-array)

12 (Y-array)

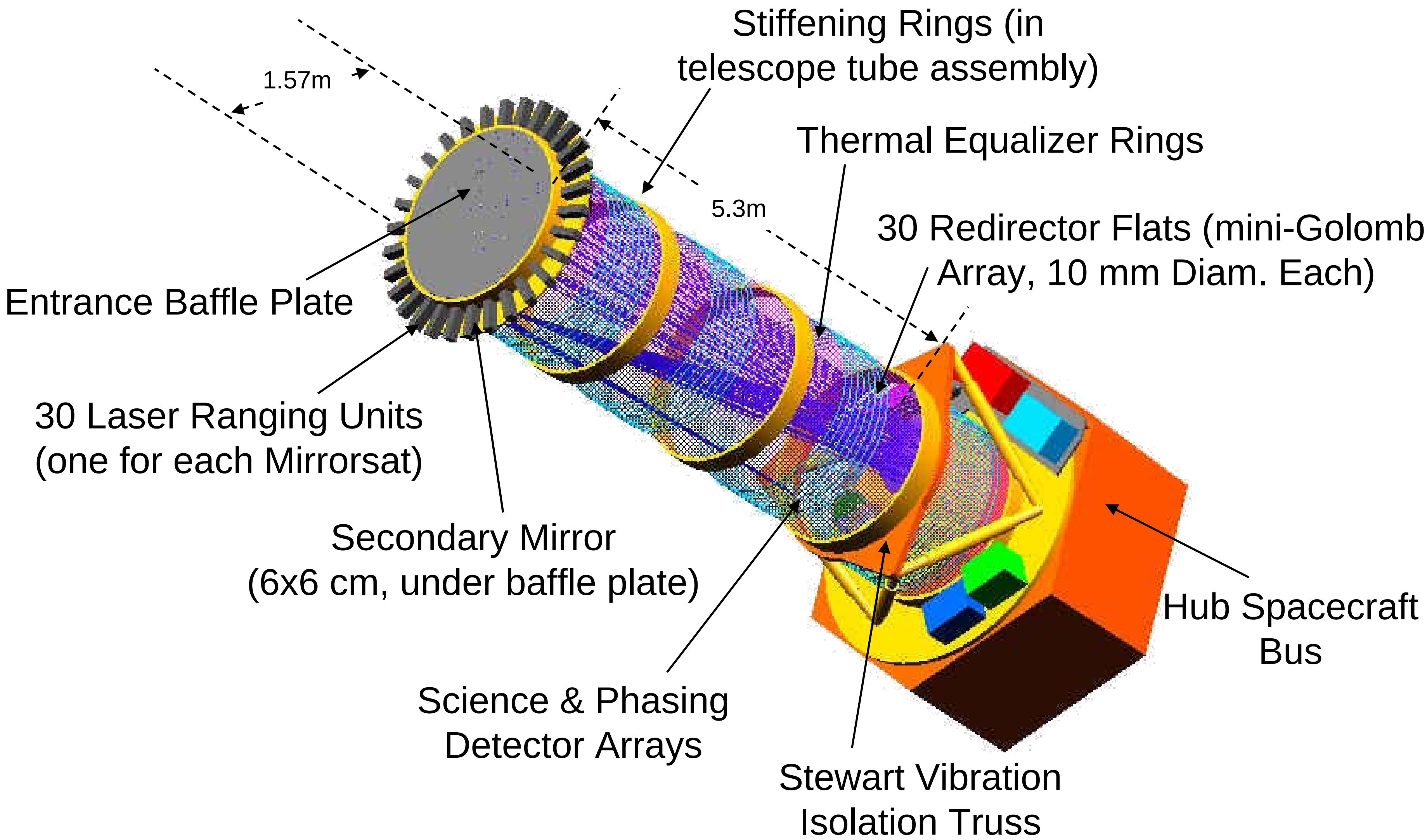
30 (Golomb Rectangle)



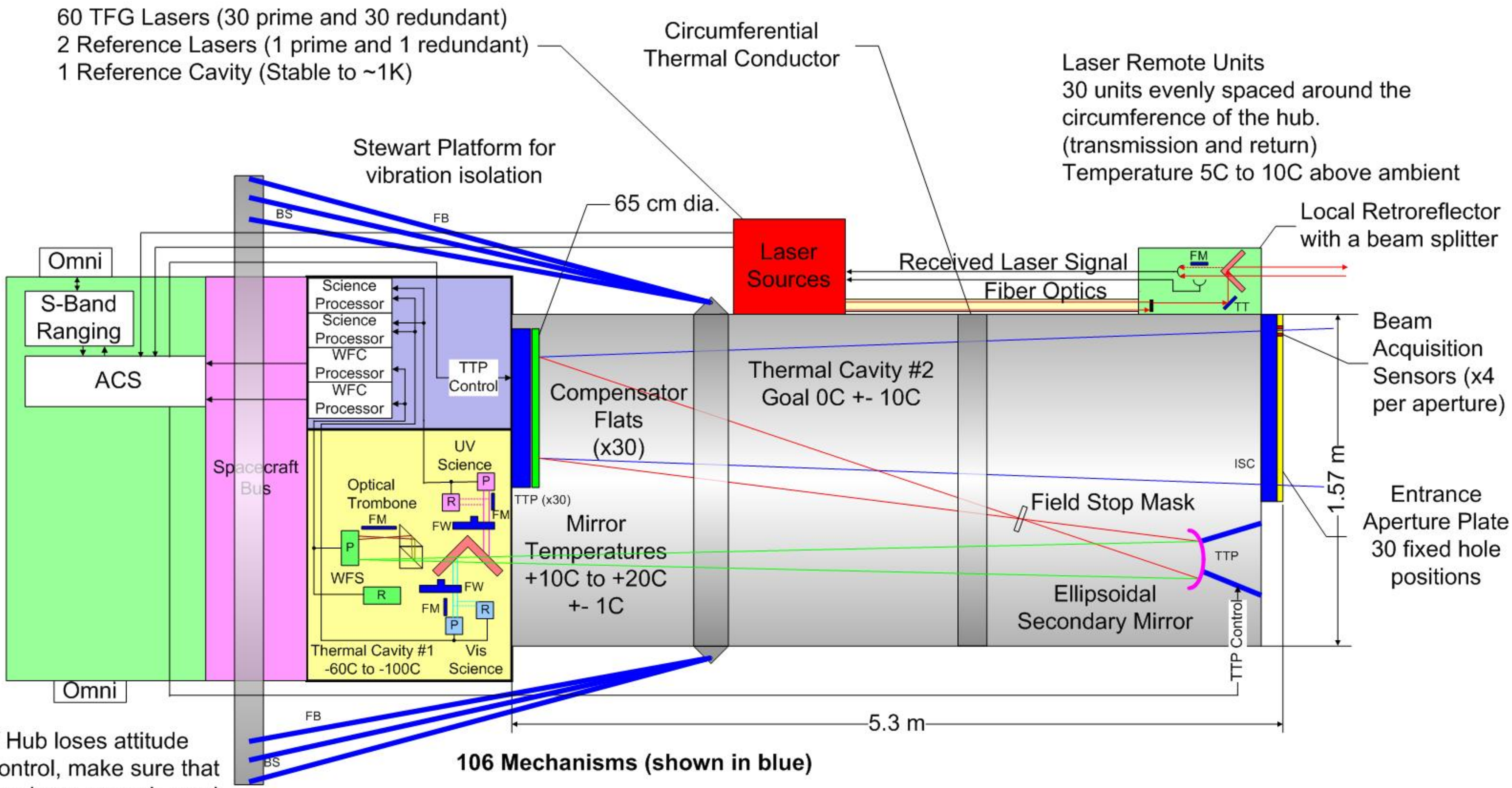
Baselines: 250 m 500 m 250 m 500 m

Simulations calculated using SISIM, written by R. Allen/J. Rajagopal, STScI

Principal Elements of SI Hub



Hub Block Diagram



If Hub loses attitude control, make sure that you have enough omni antennas to prevent loss of RF ranging to Mirrorsats.

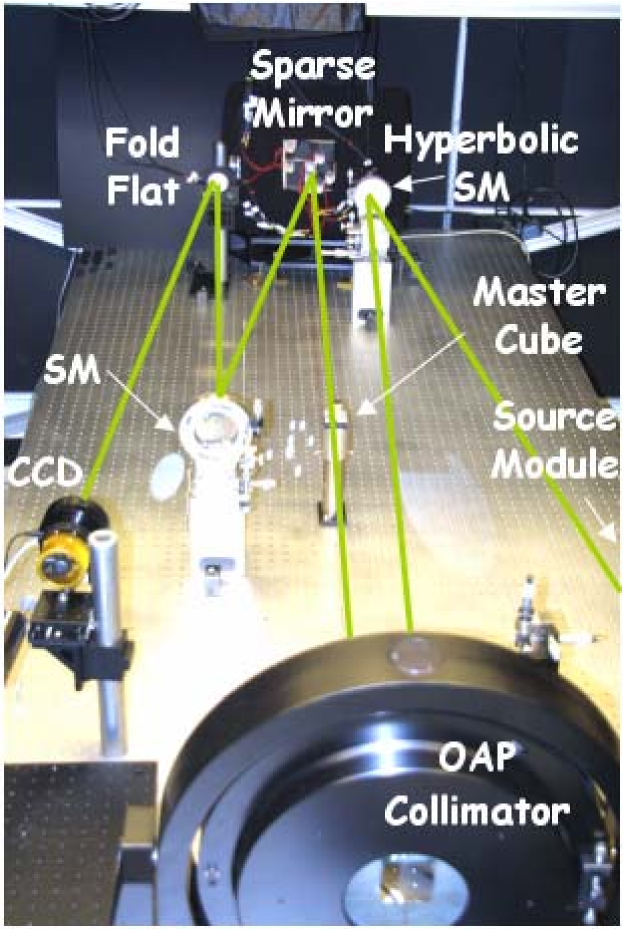
106 Mechanisms (shown in blue)

BSP Bipod Strut Mechanism (x6)
FM Flip Mirror Mechanism (x33)
ISC Internal Shutter/Cover Mechanism (x1)
TTP Tip/Tilt/Piston Mechanism (x31)
FB Frangi-Bolt Launch Lock Mechanism (x3)
FW Filter Wheel Mechanism (x2)
TT Tip/Tilt Mechanism (x30)

The GSFC Fizeau Interferometer Testbed (FIT):
Developing Closed-Loop Optical Control for Large Arrays

K. Carpenter, R. Lyon, K. Hartman/GSFC; P. Petrone, P. Dagoda, J. Marzouk/Sigma Space,
D. Mozurkewich/Seabrook Eng., T. Armstrong & X. Zhang/NRL, L. Mundy/UMD

- **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

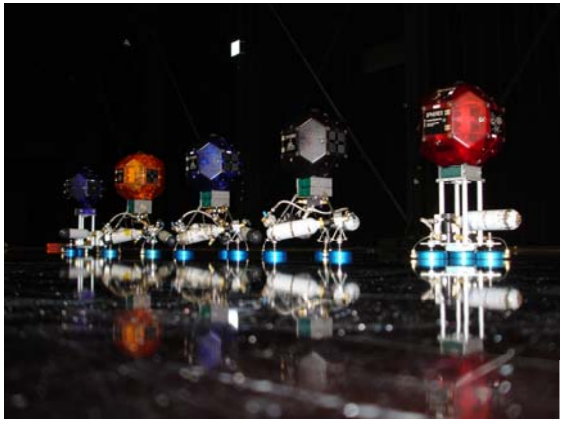


The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT)

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 (**S**ynchronized **P**osition **H**old **E**ngage and **R**eorient **E**xperimental **S**atellites) experiment on the MSFC Flat Floor Facility
  - Areas of investigation include:
    - Formation Capture (deployment)
    - Formation Maintenance
    - Formation Reconfiguration
    - Synthetic Imaging maneuvers (retargeting and reconfig.)

One SPHERES unit



Five SPHERES on air carriages on MSFC Flat Floor

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