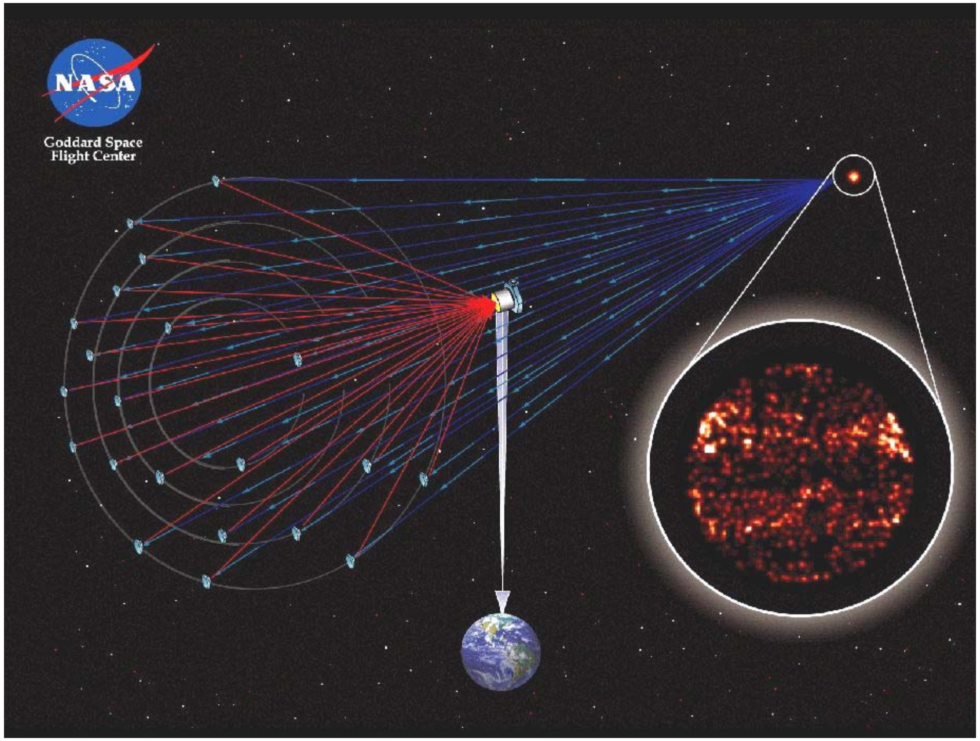
The Stellar Imager (*SI*) "Vision Mission":



A UV/optical deep-space telescope for 0.1 milli-arcsec imaging & spectroscopy of magnetic field structures that govern:

- the origin and evolution of stars and their planetary systems
- the habitability of planets
- transport processes on many scales in the Universe
- solar system space weather in the Exploration Era

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 EUD Roadmap Meeting , held March 15-16, 2005, in Greenbelt, MD

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

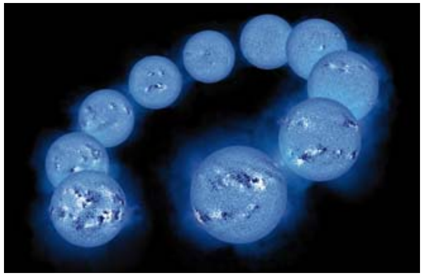
Kiepenheuer Institute
University of Aarhus

- Institutional and topical leads from these institutions include:
  - 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

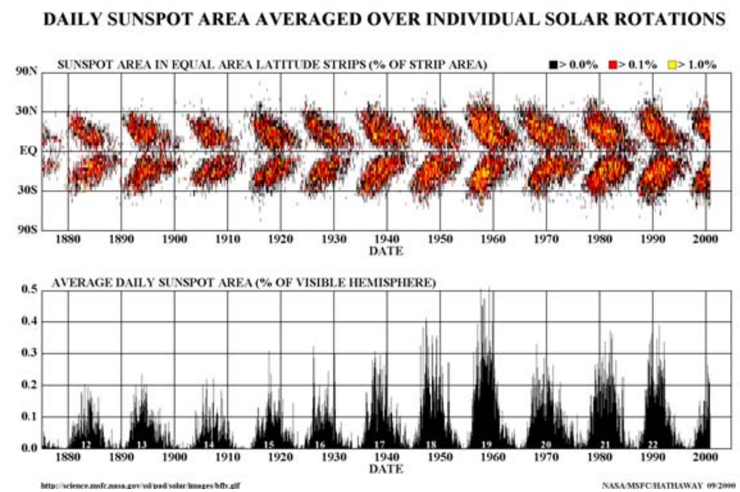
Why Stellar Imager?

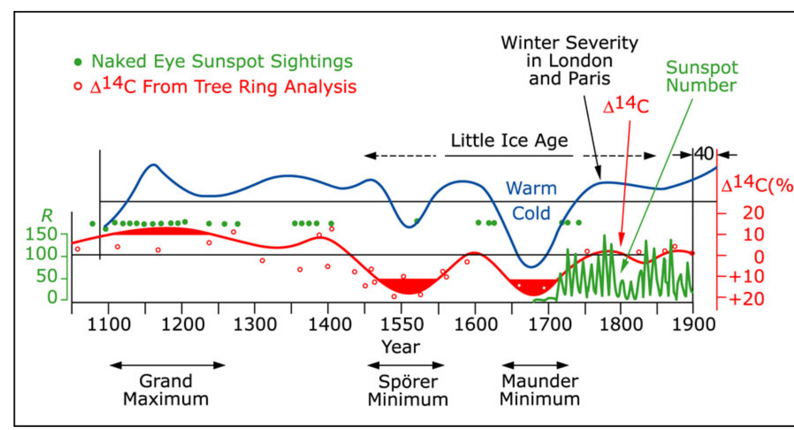


- **Magnetic fields**
  - affect the evolution of structure in the Universe and
  - drive stellar activity which is key to life's origin and survival
- **But our understanding of how magnetic fields form and evolve is currently very limited**
  - Our close-up look at the Sun has enabled the creation 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**

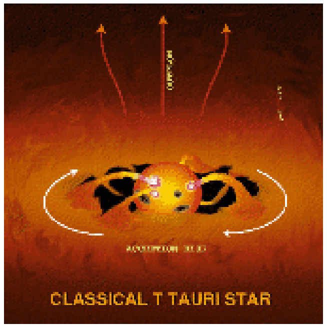
Solar-type dynamos: Key Questions

- 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?

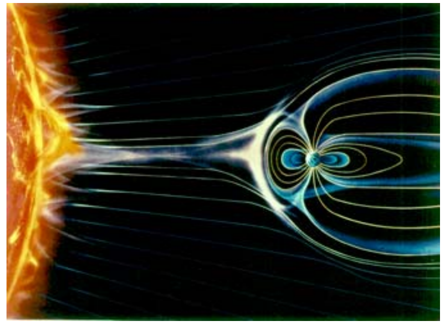




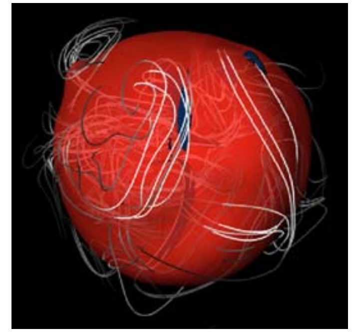
Astrophysical Magnetic Fields: Key Questions



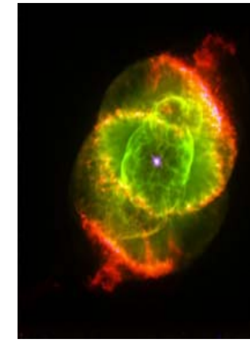
The cradle of life



Stellar activity & planets, life



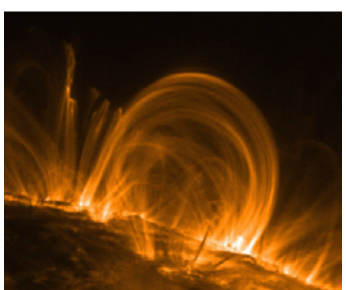
Dying giants



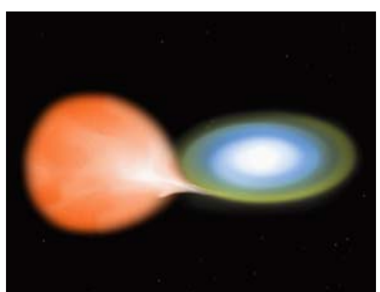
How does the dynamo evolve?

how do magnetic fields affect star & planet formation?
how do fully convective stars sustain magnetic activity?
how do magnetic fields cause and control jets?

Can we generalize stellar dynamo properties?



The Sun



Interacting binary

Accretion, jets, outflows

Accreting AGN

The *Stellar Imager (SI)*

is a long-baseline, space-based, UV-optical observatory that will provide a (sub-mas) angular resolution more than *100x that of HST*.

It will resolve for the first time the surfaces 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 stars outside solar parameters

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

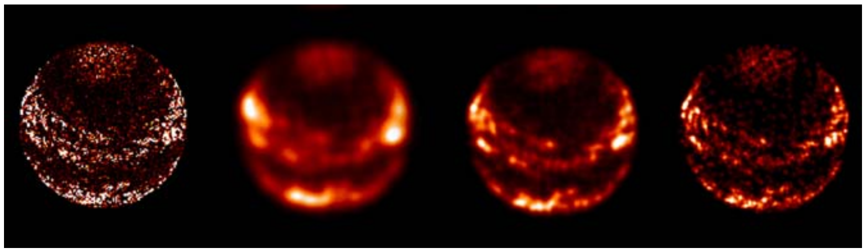
Active Galactic Nuclei
transition zone between Broad and Narrow Line Regions;
origin/orientation of jets;
distances

What Will Stellar Imager See?

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

Model

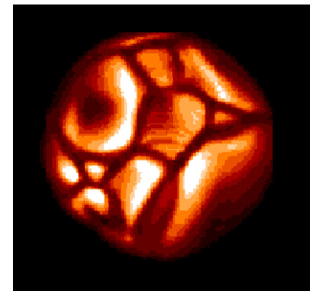
SIsim images



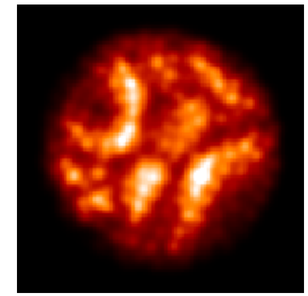
Baseline: 125m 250m 500 m

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

Model

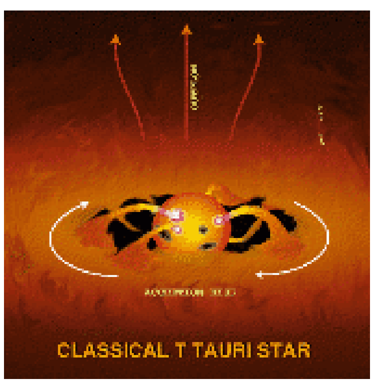


SIsim image (2mas dia)

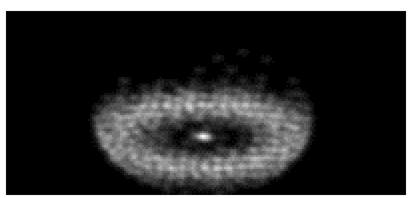


Baseline: 500 m

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



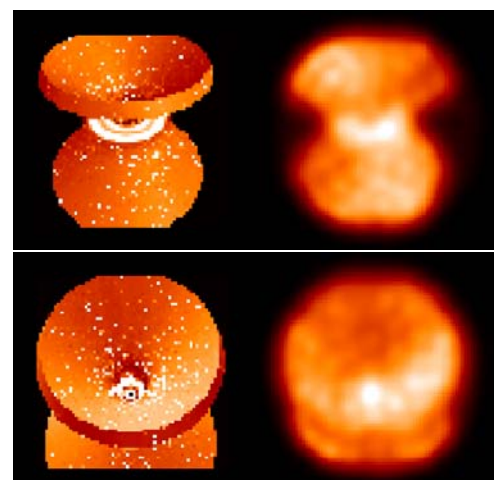
0.1 mas



SI simulation in
Ly α–fluoresced H2 lines

Baseline: 500 m

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



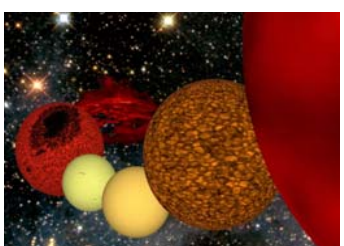
0.1 mas

model

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

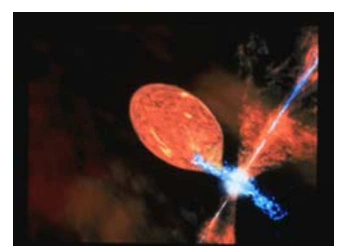
Key SI Science Goals

- **Study the evolution of stars & their magnetic dynamos by resolving patterns of surface activity & internal structures & flows in a diverse sample of stars**
  - to improve long-term forecasting of solar & stellar activity and understand the impact of stellar magnetic activity on planetary climates and the origin & maintenance of life
  - to understand the variable Sun-Earth system
- **Complete the assessment of external solar systems begun with the planet-finding and imaging missions**
  - by imaging the central stars of those systems to determine the impact of their activity on the habitability of the surrounding planets
- **Study the Universe at ultra-high angular resolution to understand**
  - the origin of stars, planetary systems, and life
  - the structure of stars and the life cycle of stars and their planetary systems
  - internal transport processes in stars at different ages, their impact on stellar evolution, and their consequences for the chemical evolution of galaxies
  - dynamo and accretion processes, mass-exchange, and mass flows in, e.g., AGN's, black hole environments, supernovae, binary stars, and highly evolved stars

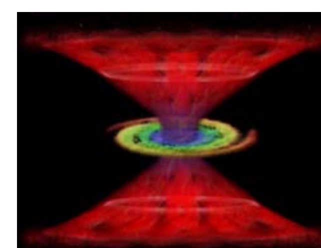



Evolution of Stars, Planets, Life

Supernovae



Accretion Jets



AGN BELR

SI and the NASA-ESA Strategies

– ***SI*** *addresses 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 SEC (SSSC/SEED)

...and the origins & evolution of structure & life in the Universe

– ***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)).

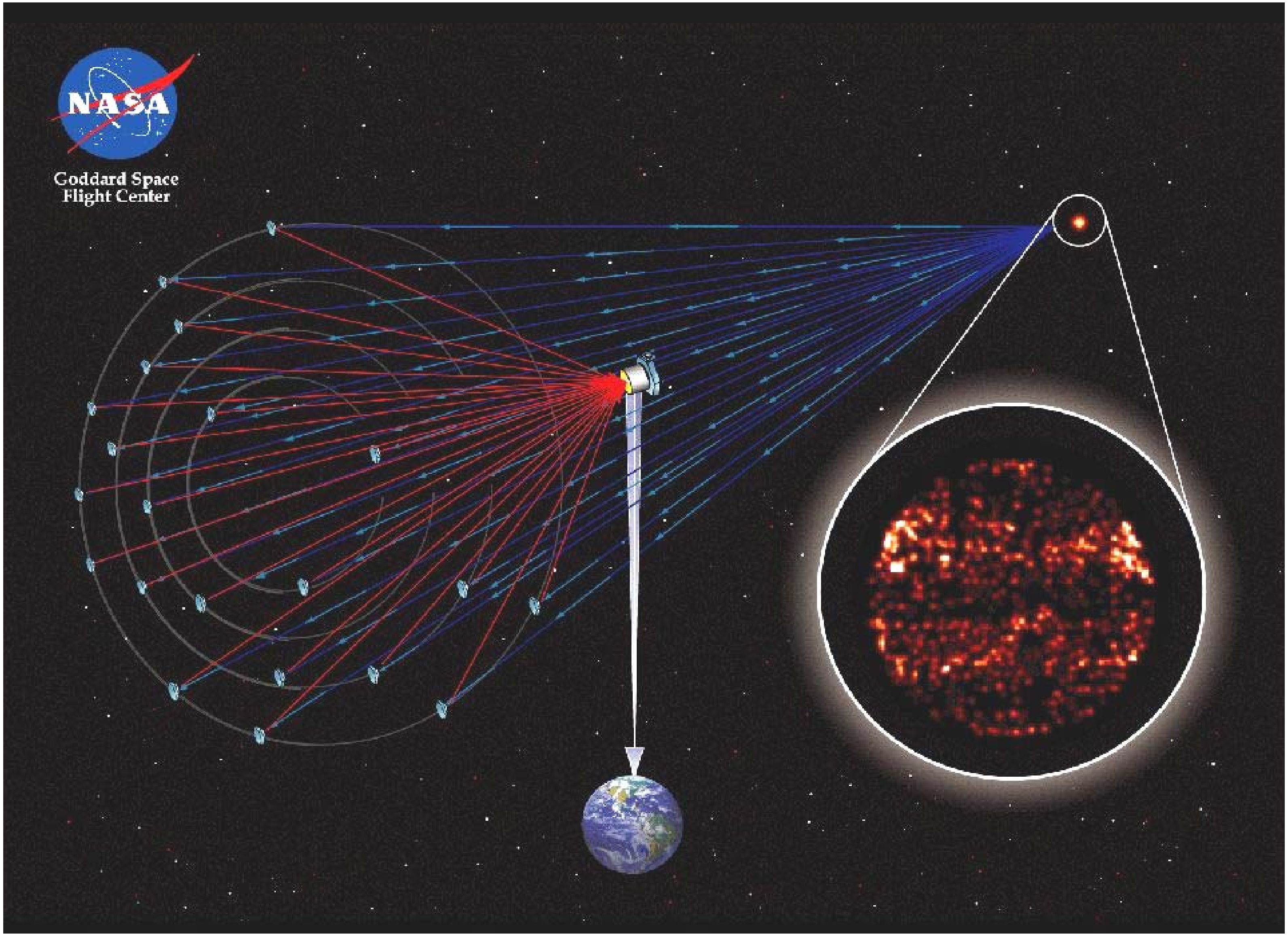
2) as a means to improve our ability to forecast space weather within our own solar system:

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.

"Strawman" Mission Concept

- Required Capabilities (1200 – 5000 Å)
  - access to UV emission lines from Ly α 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; asteroseismology)
  - angular resolution of 0.06 & 0.12 milli-arcsec at 1550 & 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
- Design
  - 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

“Strawman” Concept (con’t)



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 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)

Note: Much of this technology development is threatened due to the dissolution of Code R. It is critical for many future distributed-spacecraft missions that such development be reconstituted under Code S and/or Code T.

Precursor/Pathfinder Mission

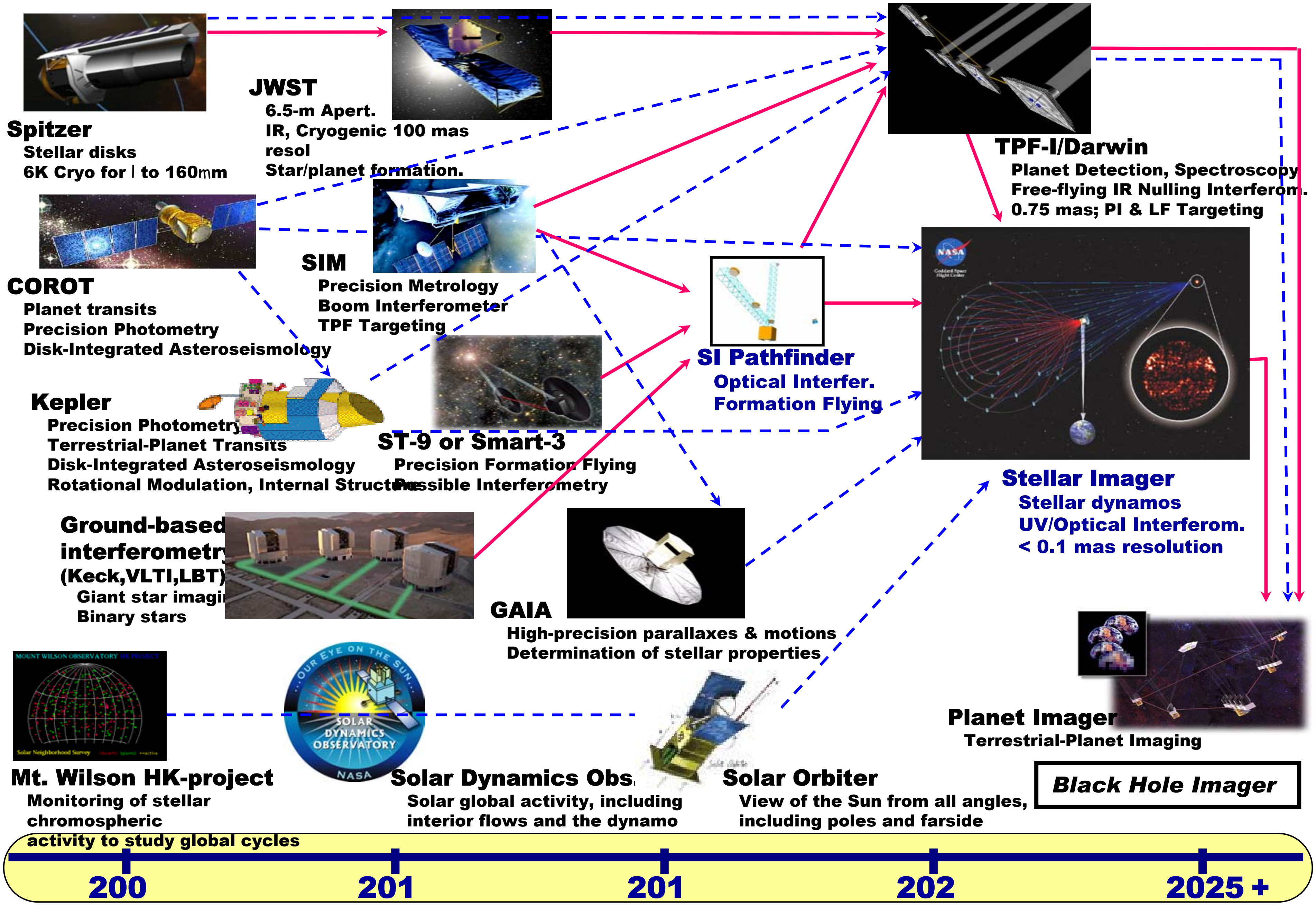
- A pathfinder mission which takes smaller technological steps is desirable to reduce mission risk and would
  - advance technologies needed for other missions in NASA strategic plans
  - will address a subset of the SI science goals

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

Science and Technology Interdependencies of SI and other Missions



Tentative Schedule

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, detectors

2006: Develop Pathfinder Concept suitable for future “Origins/Universe Probe” type opportunities

2007: Propose Pathfinder Mission

~2015: Fly pathfinder mission

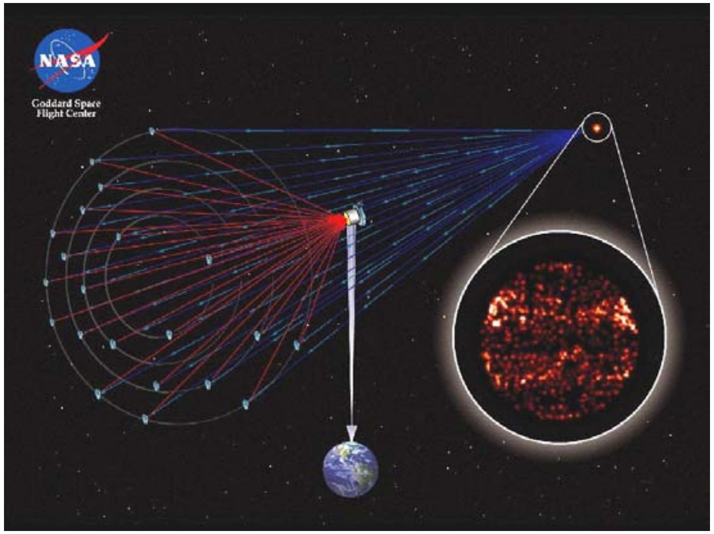
~2024: Fly full mission

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, BATC, NGST, JPL, SAO, CU to develop concept/technology
- SI presented to SEU/Origins, SSSC, APIO Roadmap Committees (Nov. 2005 →)
- 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
- Interdisciplinary nature of SI goals argue for inclusion of SI in Universe Division Roadmap, as well as in SSSC.

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 L_2
- maximum baseline ~500 m
- => 1000 pixels/stellar image
- Mission duration: ~10 years



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

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

Appendix: Supplemental Information

Diagnostics for activity and seismology

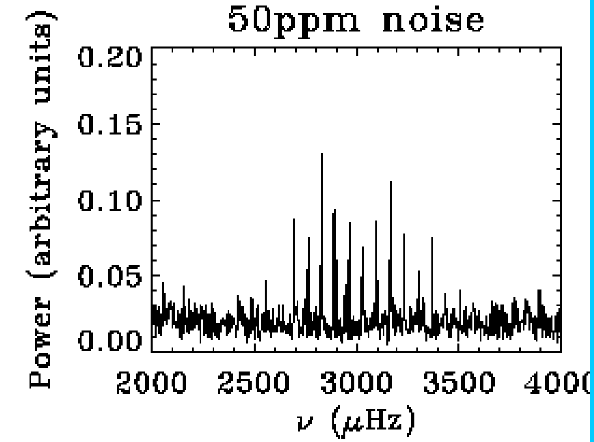
- The SI prime Science goals require
  - Imaging stellar surfaces to measure flux emergence patterns (in latitude and longitude) and flux dispersal and advection (by convection, differential rotation, and meridional circulation).
  - the use of spatially-resolved asteroseismology to measure large-scale flows on the surface and in the interior.
- which only can be met by high angular-resolution UV/optical imaging (UV for surface imaging, broad-band optical for seismology)

Technique:		**Because:**
Doppler imaging	Fails	Sources evolve well before a rotation is completed on a Sun-like star; latitude ambiguity on fast rotators
Rotational modulation	Fails	Sources evolve too fast; no latitude information; no reference level
X-ray imaging	Fails	No access to asteroseismology; too much confusion by rapid coronal evolution
Optical only imaging	Fails	Works for seismology, but not for surface imaging (Spot coverage too small on Sun-like stars; no access to surface flows as spots dissolve)
UV & optical imaging	**Succeeds**	UV ➔ High contrast to detect active regions and their dispersed patterns; Optical ➔ seismology

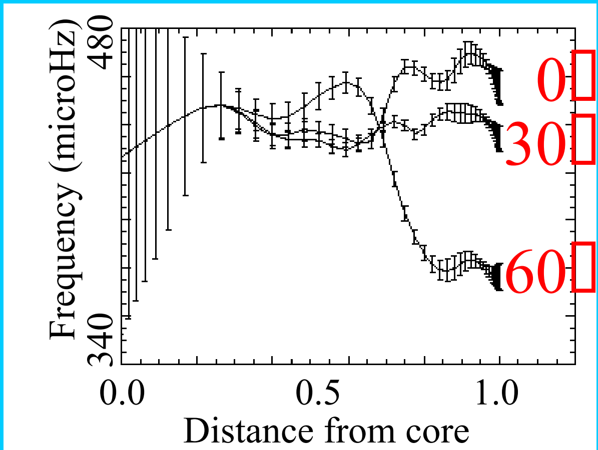
The Value of Spatially-Resolved Asteroseismology

- Stellar dynamo: internal rotation
  - Radial rotation profile in radiative interior and fairly deep layers of the convective envelope.
  - Latitude variation of near-surface rotation.
  - Measurement of properties of stellar tachoclines, presumed to be the seat of the global stellar dynamo.
- Physical quantities and transport mechanisms: internal structure
  - Measure the internal structure for the radiative interior
  - Unambiguously determine stellar ages.
  - Improve knowledge of stellar mixing processes (involving also magnetism) and gravitational settling; these uncertain factors in stellar modeling impact, e.g., Big Bang nucleosynthesis (primordial Li abundance), properties of supernova progenitors (distance scale, and stellar abundance yields into galaxies).
  - Measure the equation of state and test opacities, improving the accuracy of the distance scale of the universe, and the initial He abundance (impacts galactic chemical evolution).

With need only 40 pixels across the star to measure modes up to l=60, so that after one month on target:



This simulation shows how well a Sun-like rotation profile with depth and latitude is measured:



For Reference--SI Requirements Flow Down (11/03/04)

Science Goals

Understand the dynamo process responsible for magnetic activity in stars

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

Complete the assessment of external solar systems begun with the Planet Finding and Imaging missions by imaging the central stars and determining the impact of the activity of those stars on the habitability of the surrounding planets

Study the Universe (AGN's, QSO's, Black Holes, Super-novae, Interacting Binary Stars, hot stellar winds/non-radial pulsations, forming-stars and disks, cool evolved and long-period variable stars) at high angular/spatial resolution

→

Data Required

Empirical constraints to refine dynamo models. Specifically, for a solar-type star at 4 pc:

Observations of spatial and temporal stellar surface magnetic activity patterns in a sample of stars covering a broad range of activity level:

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

Measurement of internal stellar structure and rotation:

> Astereoseismology via optical images with 30-100 total resolution elements over a stellar disk to measure non-radial resonant waves with short integration times minutes (dwarfs) to hours (giants)

Long-mission lifetime (>10 years) needed to provide observations over significant fraction of stellar activity cycles

→

Measurement Capabilities

Angular Resolution
- 0.1 mas

Spectral Range
- 1500 - 6000 Å

Field of View
- ~ 4 mas

Flux Threshold at 1550 Å
- 1×10^{-13} ergs/cm^2/s

Observations
- several dozen solar-type stars observed repeatedly over mission lifetime
- month-long seismology campaigns on select targets

↓

Engineering Implications

Baselines from 100 to 500 m

>20 primary optical elements of > 1 m in diameter with UV quality smoothness

Fizeau Beam combination

Path Length Control to 3 nm

Aspect Control to 30 μarcsec

Orientation +/- 20deg 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)

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

mass-production of "mirrorsat" spacecraft

SI Design Reference Mission (DRM)

- Developed a program to produce SI DRM's under various assumptions to enable us to estimate resource needs and observatory capabilities over it's lifetime for various assumptions
- Use of this tool has demonstrated that there are sufficient available science targets to produce an efficient observing program with tolerable # of slews, slew lengths, and desired observing cadences and reasonable demands upon resources (e.g. propellent)
- Assumptions
  - SI will point within 20 deg of the great circle perpendicular to the Sun-SI line (70<beta<110 deg)
  - SI will slew with constant acceleration ➔ slew time ~ sqrt(slew distance)
  - Max slew rate = 10 deg/hr
  - 1 hour overhead to settle on and acquire new target
- Input parameters
  - Targets
    - High priority targets: 20 stars, 50% observed daily for a month
    - Additional targets: ~50 including, e.g., non-solar type stars, AGN's with 1-10 observations/month
    - Extended list of Solar-like & planet-harboring stars: ~350 stars to provide scheduling flexibility, observed with longer cadences
  - Slew rates, Beta limits, Mission start date, Overhead time, Initial SI pointing
- Typical observing efficiency ~ 50%

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

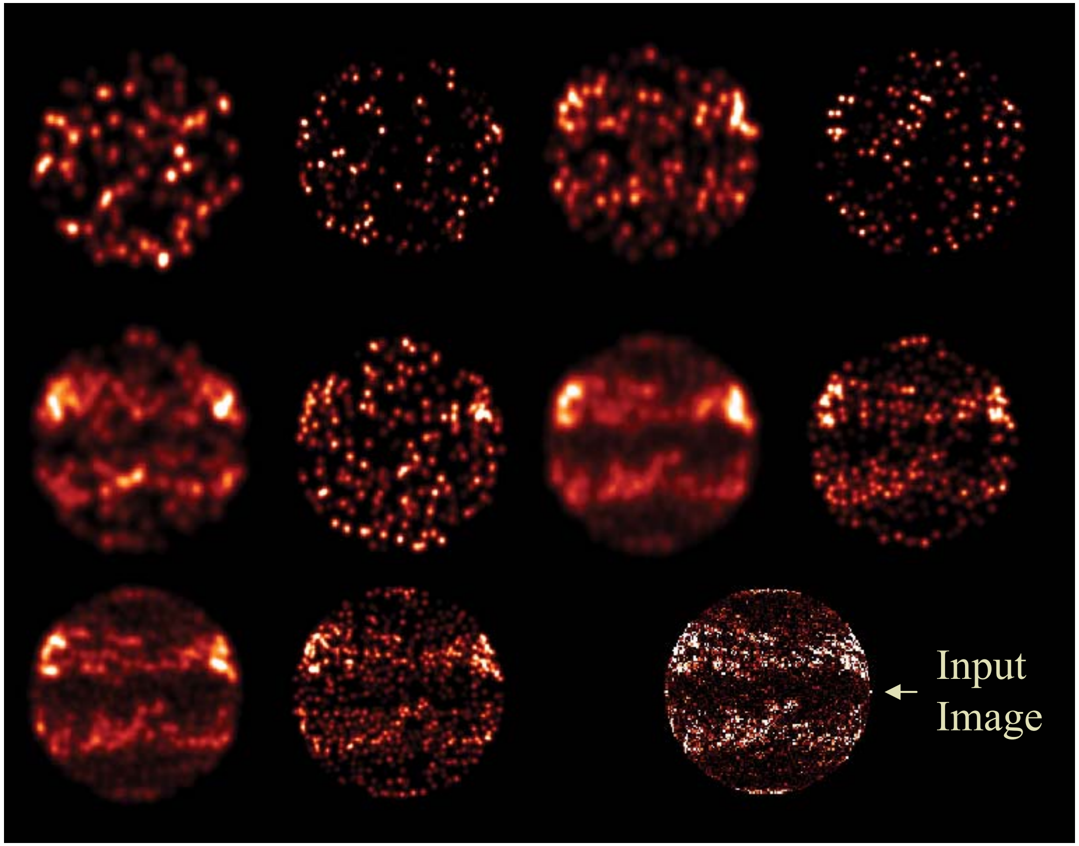
"Snapshots" (no rotations)   (24 array rotations)

 # elements (layout)

6 (Y-array)

12 (Y-array)

30 (Golomb Rectangle)



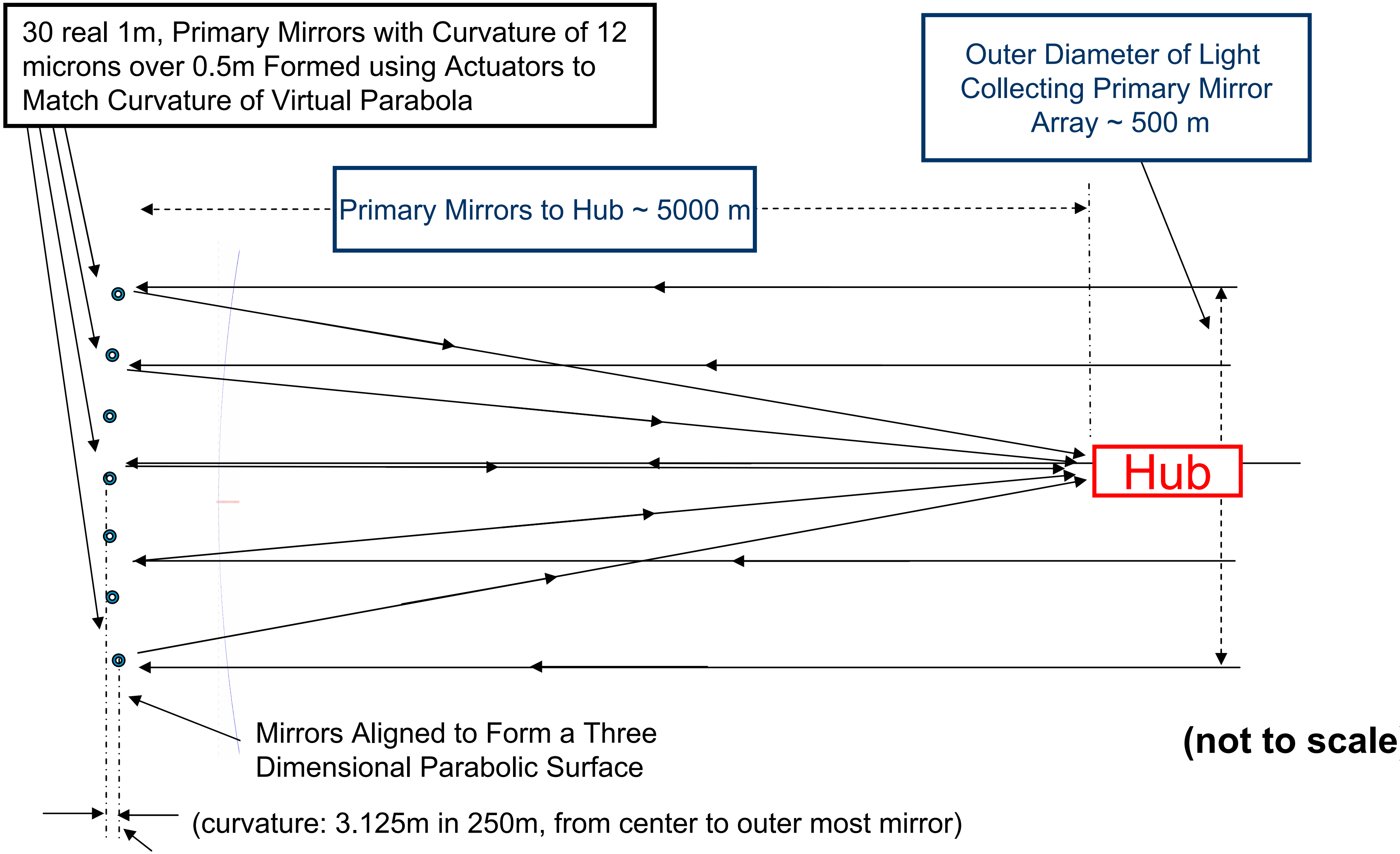
Baselines: 250 m 500 m 250 m 500 m

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

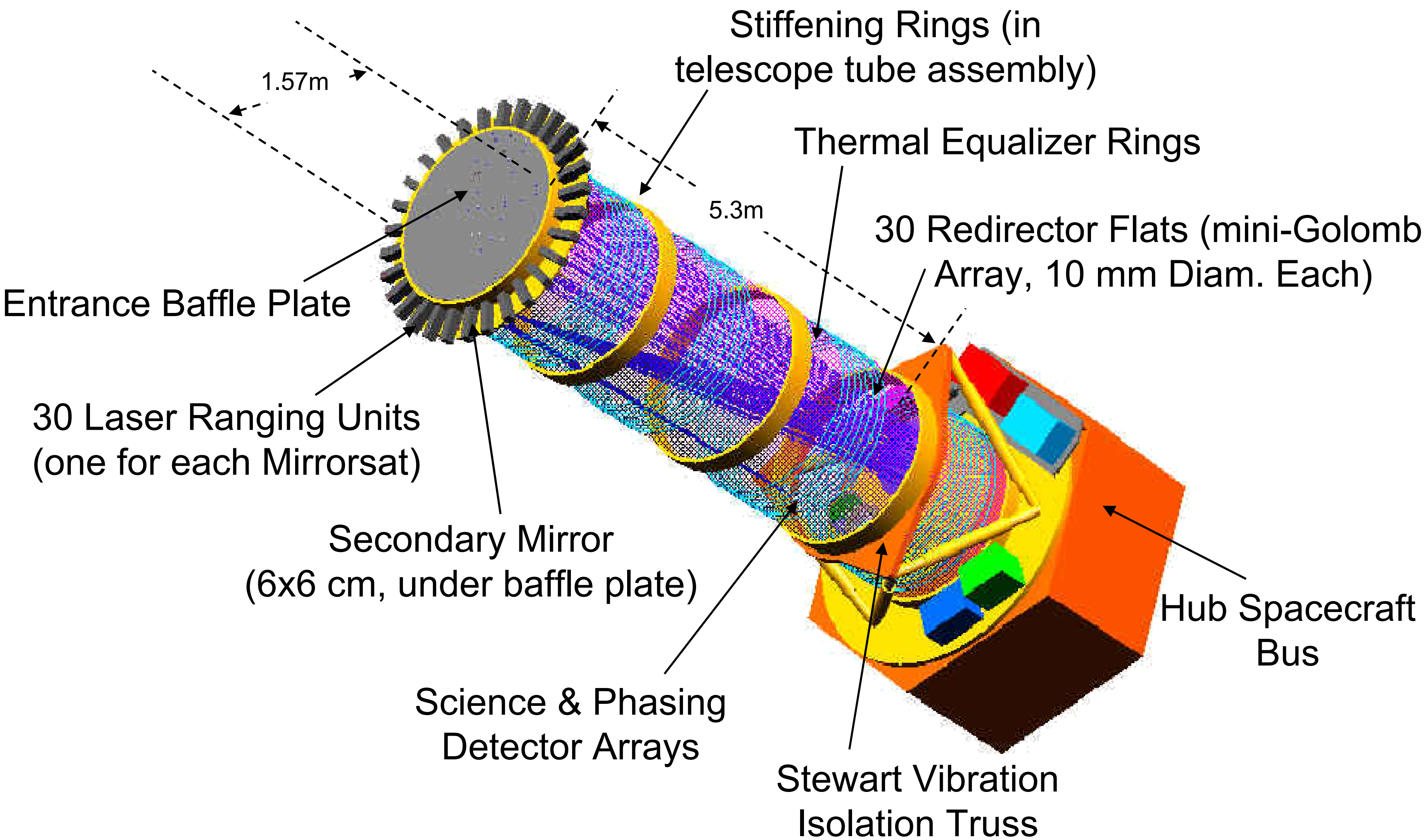
Alternative Architectures (Recent IMDC/ISAL Studies)

- Three designs are being examined by the SI Vision Team
- All utilize a large array of primary mirrors (~30) which send light to a beam-combining hub
- Differences are in how the beams are combined and mostly effect hub design, not overall architecture
  - Classical Fizeau with large focal-plane detectors (baseline design)
  - Hybrid Hypertelescope which accepts partial pupil densification in order to maintain use of non-redundant array
  - Fizeau design with remapping of beams from 2D to 1D non-redundant array
- Trades involve system sensitivity, spectroscopic capabilities, and path-length maintenance requirements
- There may be large advantages to flying more than 1 hub: both critical-path redundancy and major observing efficiency improvements (additional hubs can be pre-positioned for next segment of observing schedule, while observations being acquired with first hub)

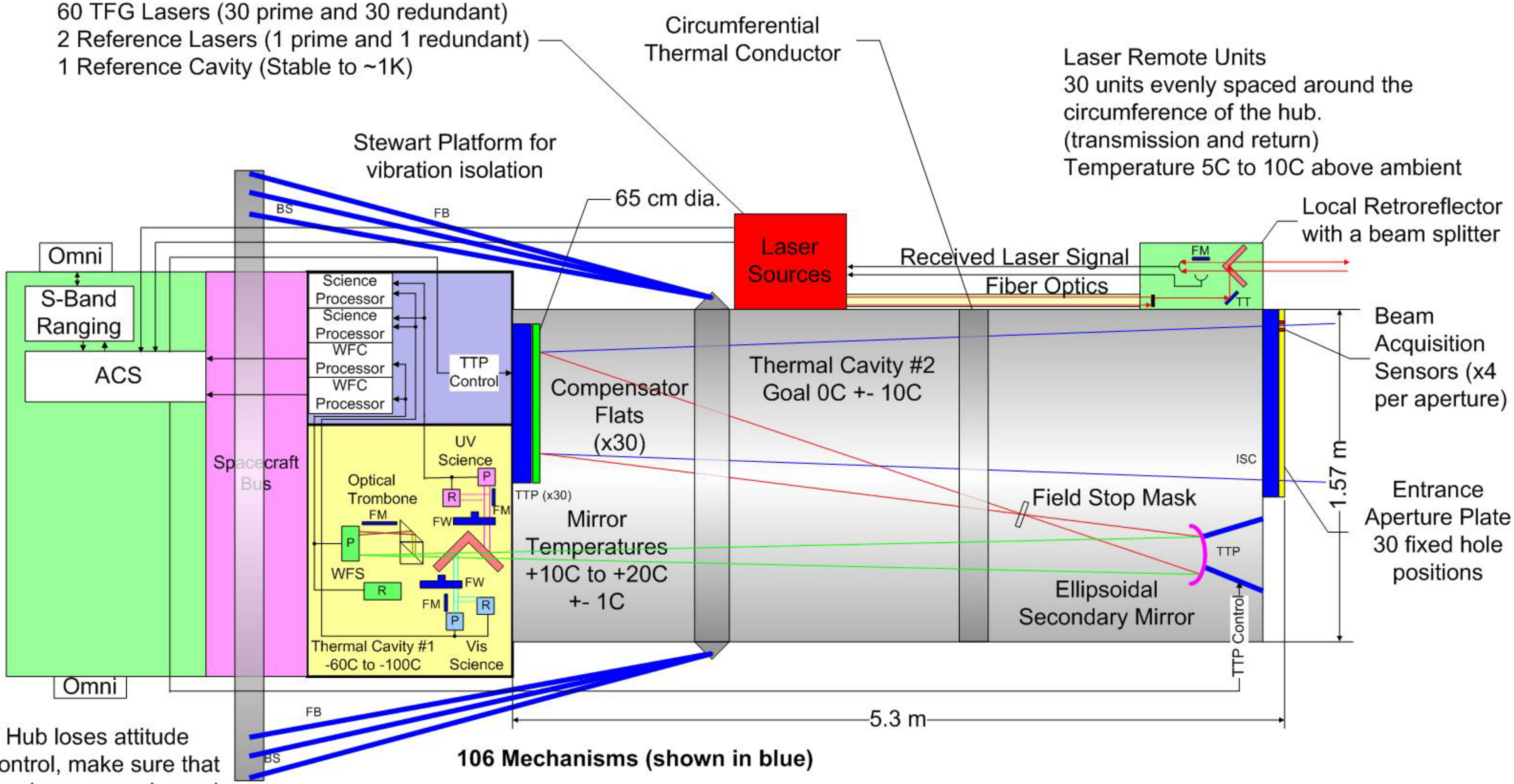
SI Cross-Sectional Schematic



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)