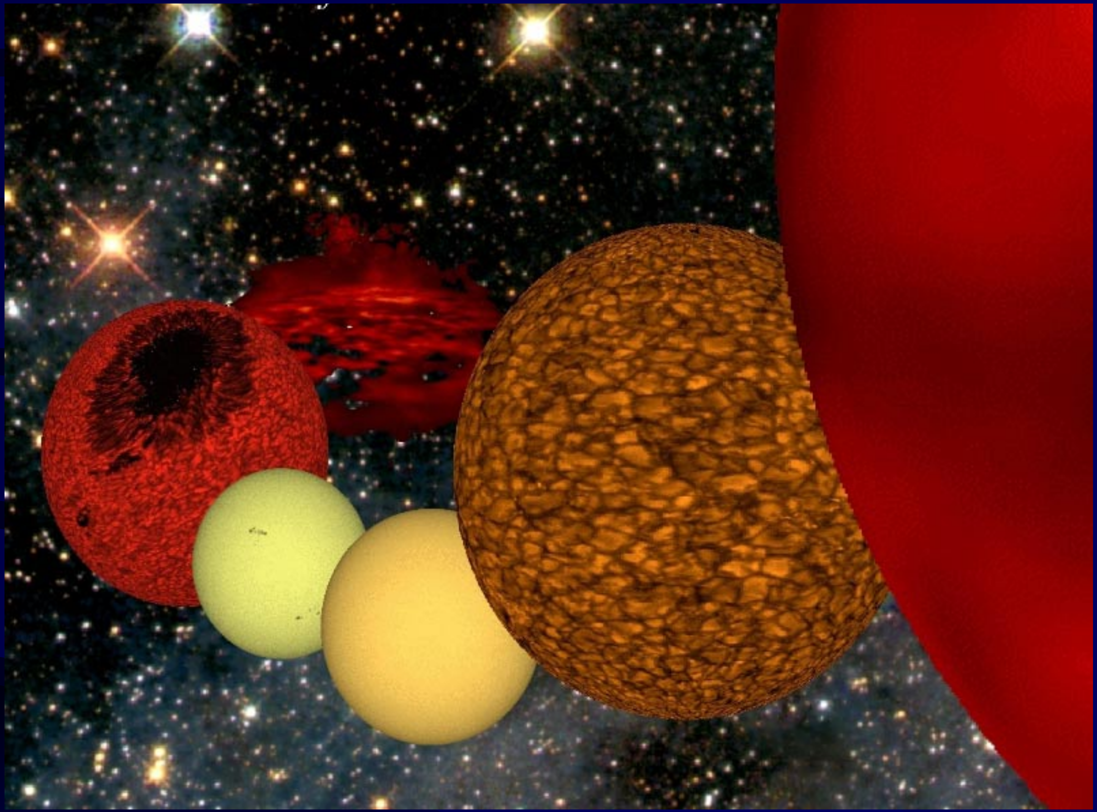
Formation Flying and The Stellar Imager (*SI*) Mission Concept



Kenneth G. Carpenter
(NASA/GSFC)

Presented at the February 5-6, 2003 ST9 Workshop in Washington, DC

Mission Concept Development Team

- Mission concept under development by NASA/GSFC in collaboration with LMATC, NRL/NPOI, STScI, UMD, CfA
  - NASA-GSFC: Ken Carpenter (Study Lead), Rick Lyon , GregSolyar/UMBC, Joe Marzouk/ΣSpace, Lisa Mazzuca, Bill Danchi, Susan Neff
  - LMMS/ATC: Carolus Schrijver (Science Lead)
  - NRL/NPOI: Tom Armstrong, Dave Mozurkewich, Tom Pauls, Xiaolei Zhang
  - STScI: Ron Allen, Jay Rajagopal
  - UMD: Lee Mundy
  - CfA: Margarita Karovska
- Consultants
  - U Vienna: Klaus Strassmeier, U Aarhus: Jörgen Christensen-Dalsgaard, Kiepenheuer Inst: Oscar Van der Lühe, Catholic U: Fred Bruhweiler , U. Colorado: Alex Brown, Jeff Linsky, Jon Morse, BASG: Steve Kilston, CfA: Andrea Dupree, Lee Hartmann, MWO: Sallie Baliunas, SUNY: Fred Walter, Yale U: Pierre Demarque, GSFC: John Mather, Keith Gendreau, Dave Leisawitz, Juan Roman

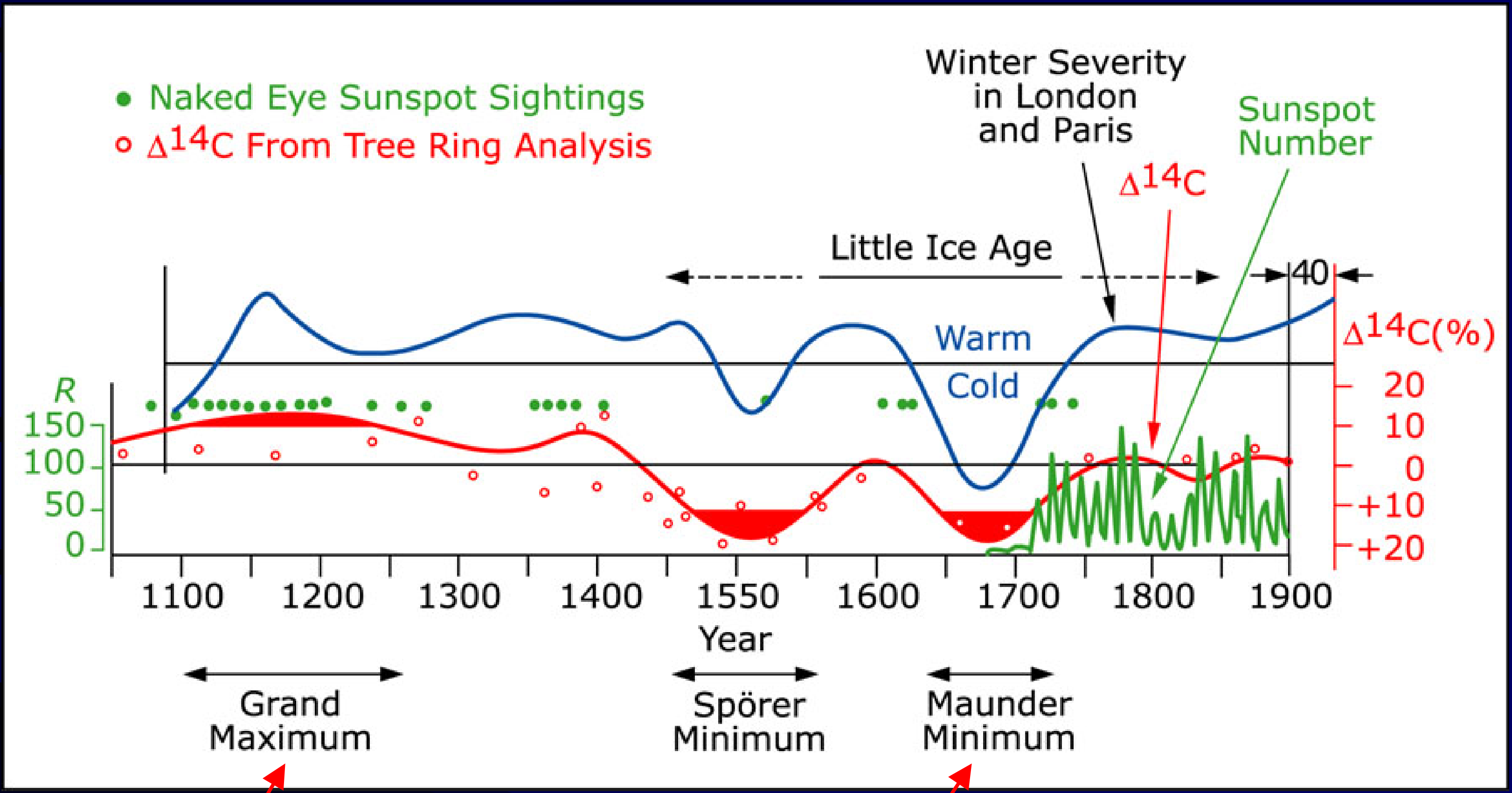
Science Context for *SI*: The Importance of Understanding Stars and Stellar Dynamos

- The Sun is only one of many classes of stars, but our close-up view of the Sun has enabled discoveries that have repeatedly revolutionized physics and astrophysics
  - existence of helium, role of nuclear fusion, convective envelopes, neutrino deficit
  - importance of non-linear, non-local processes (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 and induces associated activity which makes stars ever-changing and "dynamic". The Dynamo:
  - slows the rotation of collapsing cloud, enabling star formation
  - couples evolution of star and pre-planetary disk
  - results in energetic radiation => formation (& destruction) of complex molecules
  - governs the habitability of the biosphere through space weather and its effect on planetary climate (via high-energy particle winds, magnetic fields, and radiation)

Understanding stars and the dynamo process in general is the foundation for understanding the Universe and the origin and continued existence of life within it

Effects of Solar Variations

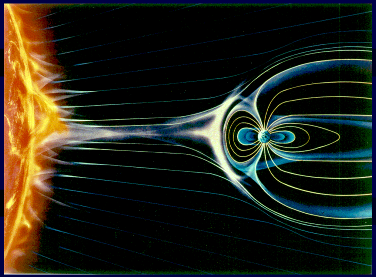


“global warming”, aggravating greenhouse effect

crop failures, July skating on the Thames

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

Stellar Activity is Key to Understanding Life in the Universe and Earth's habitability
BUT



There is no model of solar & stellar magnetic activity that predicts the level of stellar 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 Sparse Aperture Telescope / Fizeau Interferometer designed to address this problem by

enabling the high angular resolution surface and sub-surface imaging

of a broad sample of stars

needed to constrain & refine dynamo/activity models

Primary Science Goals

- Study spatial and temporal stellar magnetic activity patterns in stars representing a broad range of activity
  - Enable improved forecasting of solar activity on time scales of days to centuries
  - Understand the impact of stellar magnetic activity on planetary climates and astrobiology
- Measure internal stellar structure and rotation
- Complete the assessment of external solar systems
  - image the central stars
  - determine the impact of the activity of those stars on the habitability of the surrounding planets

Design Requirements

Requirements for imaging of stellar surface activity

– UV images: surface manifestations of dynamo
  - visible-light dark starspots small/low contrast in most stars - poor choice
  - plages are high-contrast bright spots seen in Mg II h&k 2800 A, C IV 1550 A UV emission ==> ideal activity diagnostics
  - 1000 total resolution elements

– modest integration times (~ hours for dwarfs to days for giants)
  - 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, hours for giant stars)
  - broadband optical wavelengths to get sufficiently high fluxes

– Low-resolution imaging to measure non-radial resonant waves
  - 30-100 total resolution elements

Flexible interferometer configuration required for image synthesis

“Strawman” Full-SI Mission Concept

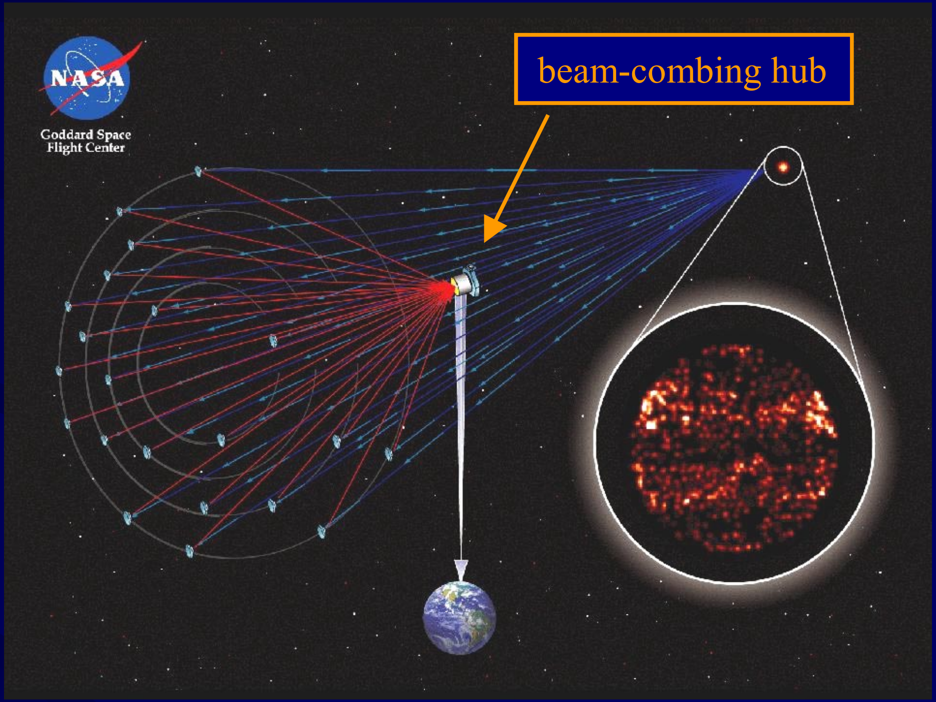
- a 0.5 km diameter space-based UV-optical Fizeau Interferometer
  - located near the sun-earth L2 point to enable precision formation flying

10 - 30 primary mirrors fly on “virtual” spherical surface with 130 km ROC

Capabilities Provided

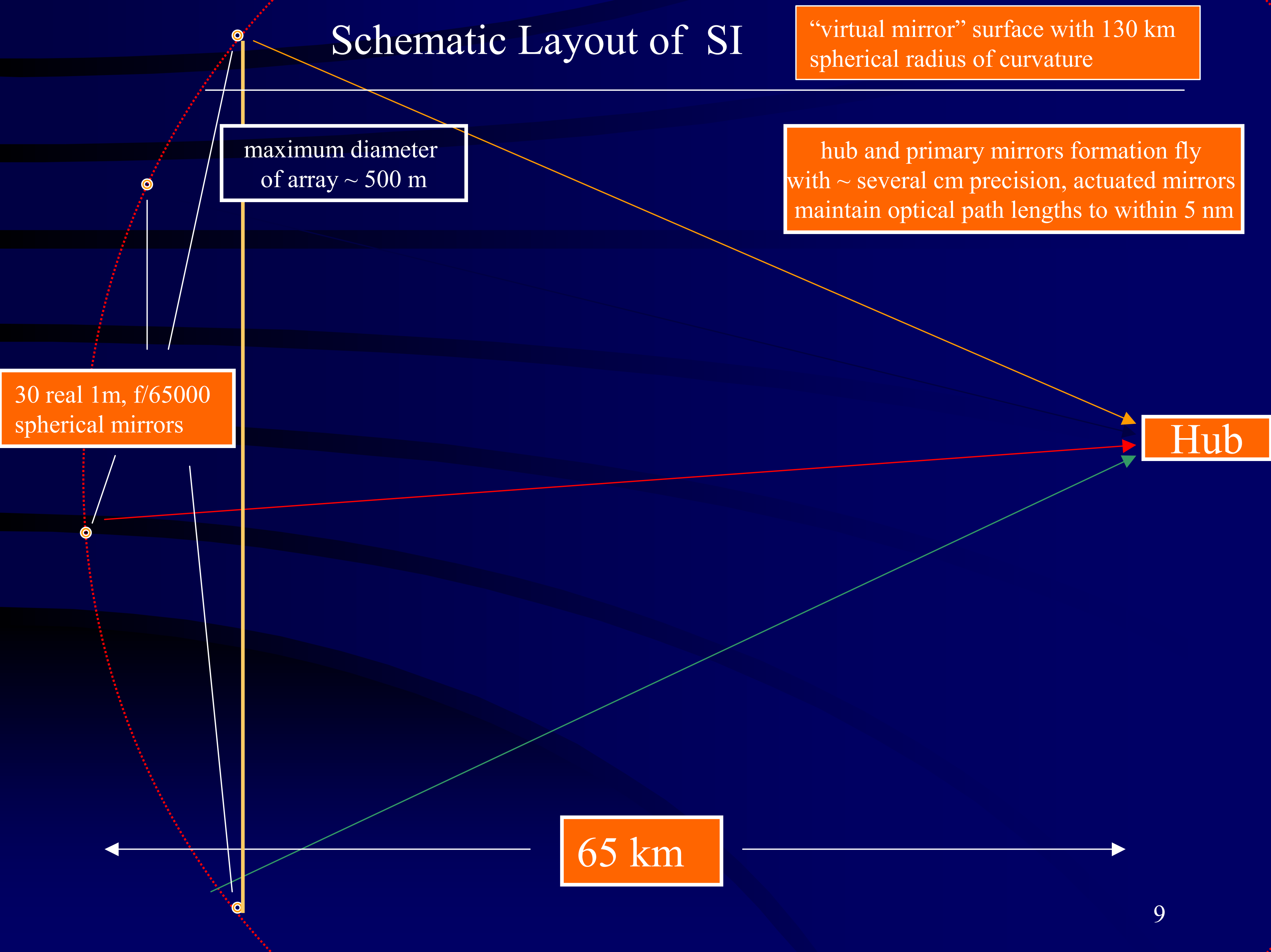
- an angular resolution of 60 & 120 micro-arcsec at 1550 & 2800 Å
- ~ 1000 pixels of resolution over the surface of nearby dwarf stars
- observations in
  - ~10-Ångstrom UV pass bands
    - C IV (100,000 K)
    - Mg II h&k (10,000 K)
  - broadband, near-UV or optical continuum (3,000-10,000 K)
- a long-term (> 10 year) mission to study stellar activity cycles:
  - individual telescopes/central hub can be refurbished or replaced

hub and primary mirrors formation fly with ~ cm precision, mirror actuators maintain optical path lengths to within 5 nm

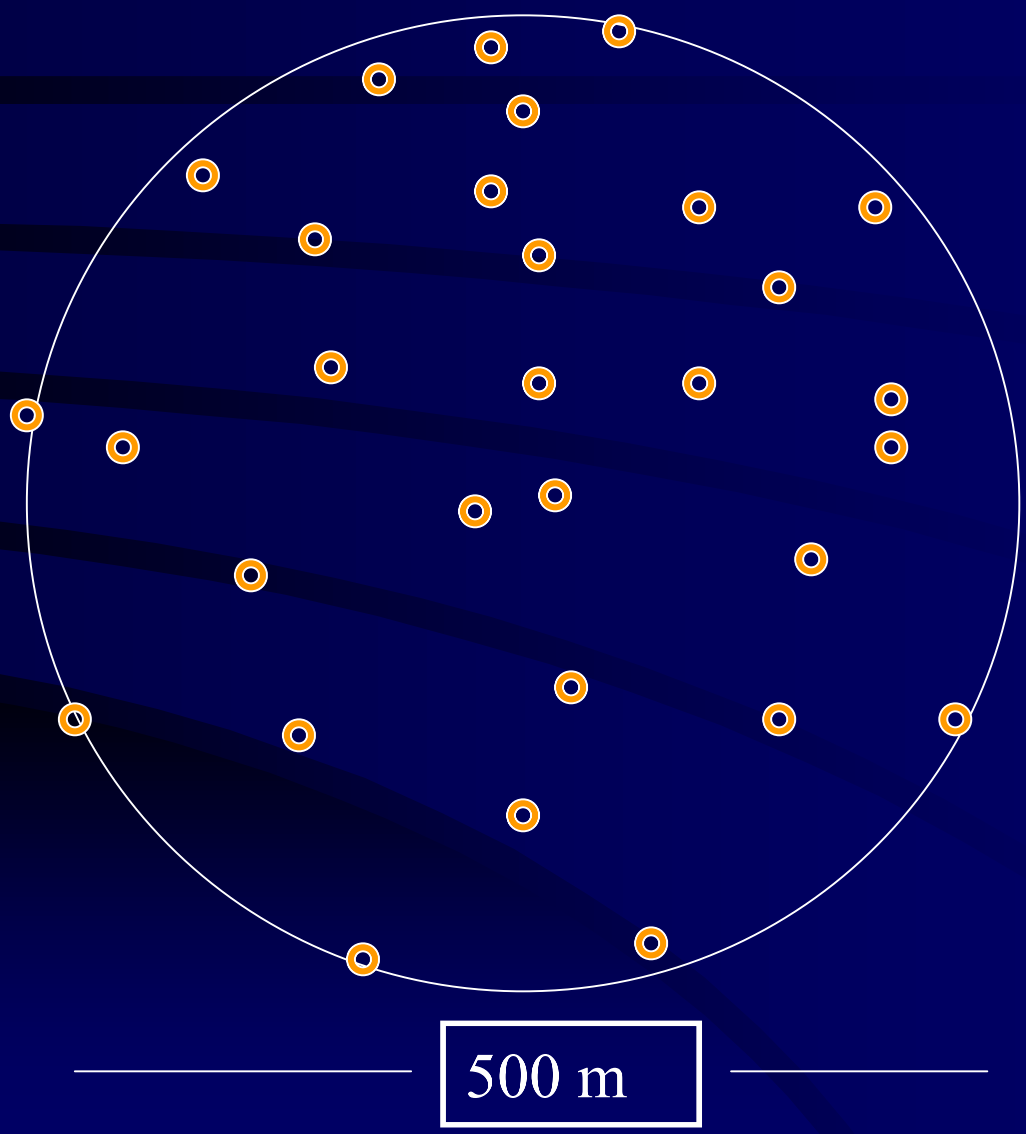


approximate distance to hub from center of array is 65 km

Schematic Layout of SI



Representative view of SI from direction of target



Mirrors are randomly distributed inside 0.5 km circle, with minimal duplication of baselines. Exact locations do not matter as long as baselines are non-redundant.

Simulated Interferometric Stellar Images

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

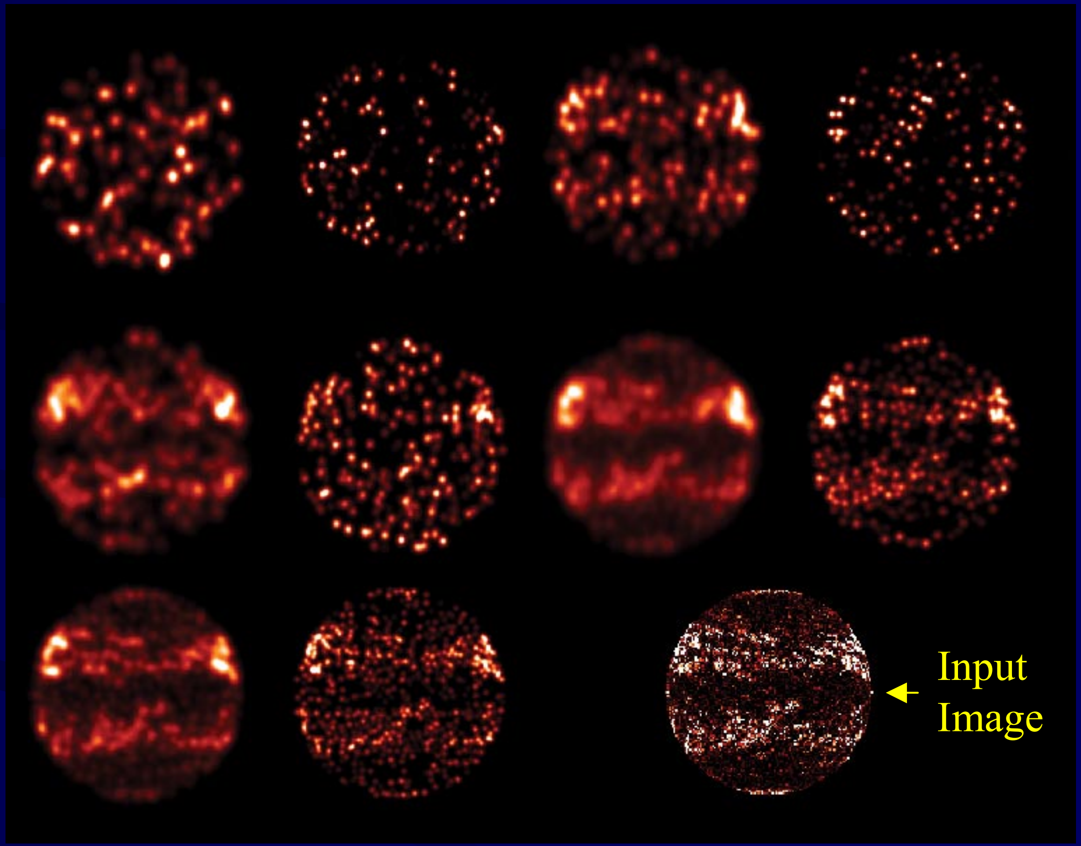
 # elements

- simulations computed with SISIM (Allen & Rajagopal)
- computed in the light of CIV (1550 A), of solar star at 4pc
- first two rows: Y-configuration
- last row assume 30 elements arranged in a low-redundancy "Golomb rectangle" (Golomb & Taylor, IEEE Trans. Info. Theo., 28, #4, 600, 1982)

6

12

30



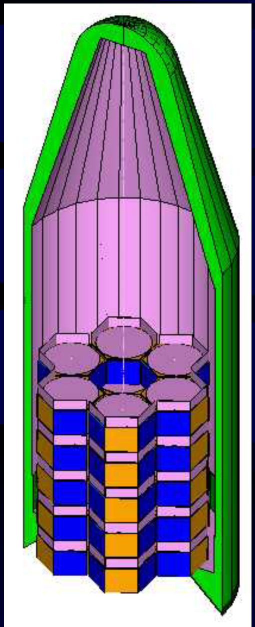
Baselines: 250 m 500 m 250 m 500 m

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

Conclusion: 30 static elements sufficient to adequately synthesize this stellar image. Alternatively, fewer elements can be used with a large number of reconfigurations.

GSFC IMDC "Full SI" Mission Study

- Baseline concept studied by GSFC Integrated Mission Design Center (IMDC)
  - 30 "mirrorsats" formation flying with beam-combining hub
  - control primary mirrors to 5 nm, rather than use optical delay lines for fine tuning
  - Fizeau interferometer: 0.5 km max. baseline, 65 km focal length



Moderate Challenges

dual launch of Delta IV + Delta III 3940-11

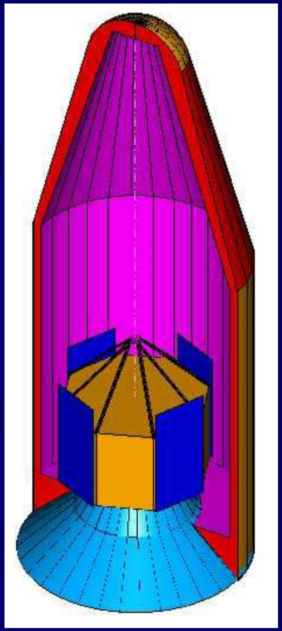
power systems: solar cells must be *body-mounted* to avoid unacceptable impact on precision formation-flying, battery life/storage a concern

propulsion: use Hall-Effect Thrusters (HET) or Pulsed-Plasma Thrusters (PPT) for mN-N level thrust
use Field Emission Electric Propulsion (FEEP's) for fine-control at μN thrust levels

operations concept: autonomous control except for command uploads and anomaly resolution

thermal: main concern is keeping mirrors isothermal

communications:
mirrorsats talk to hub and each other, hub talks to earth
contingency: mirrorsats can be commanded from earth
enhancement: central communications hub at L2



IMDC Results: The Technological "Tall Poles"

- precision metrology and formation-flying: 3-level approach envisioned
  - rough formation control (to m's): radio frequency ranging and thrusters
  - intermediate control of s/c (to cm's): modulated laser ranging+low-thrust actuation
  - fine control of mirrors/sat's (to nm's): feedback from science data system (wavefront sensing and control)
- long mission lifetime requirement
  - need to fly additional backup mirrorsats to put into operating array as failures occur
  - hub will have redundant components, but may need backup hub

- most important "enabling technologies" needing development
  - **Deployment/initial positioning of elements in large formations**
  - **Metrology and autonomous nm-level control of many-element formations over kilometer scales**
  - Aspect control to 10's of μarcsecs
  - 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)

Precursor/Pathfinder Mission

- Challenges suggest: a pathfinder mission which takes smaller technological steps and produces science results sooner is desirable
  – would advance technologies needed for other missions in NASA strategic plans

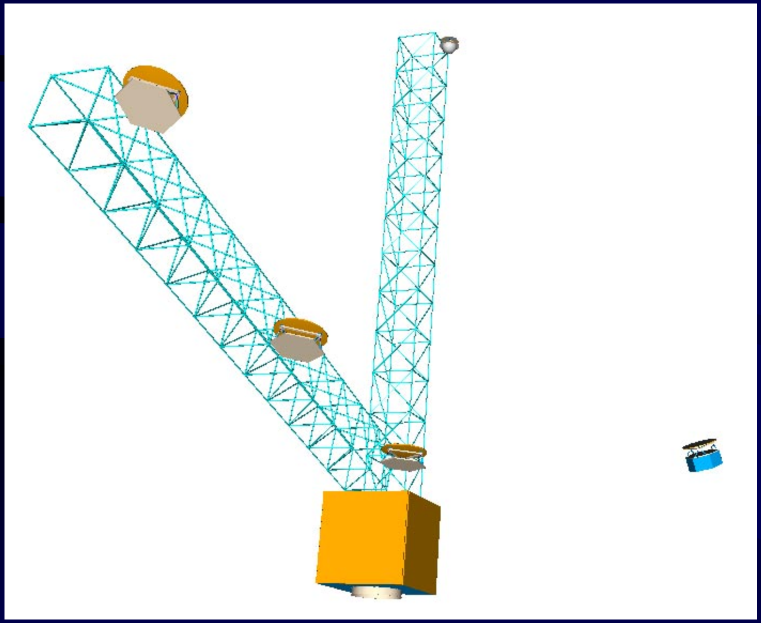
Desirable characteristics of such a mission

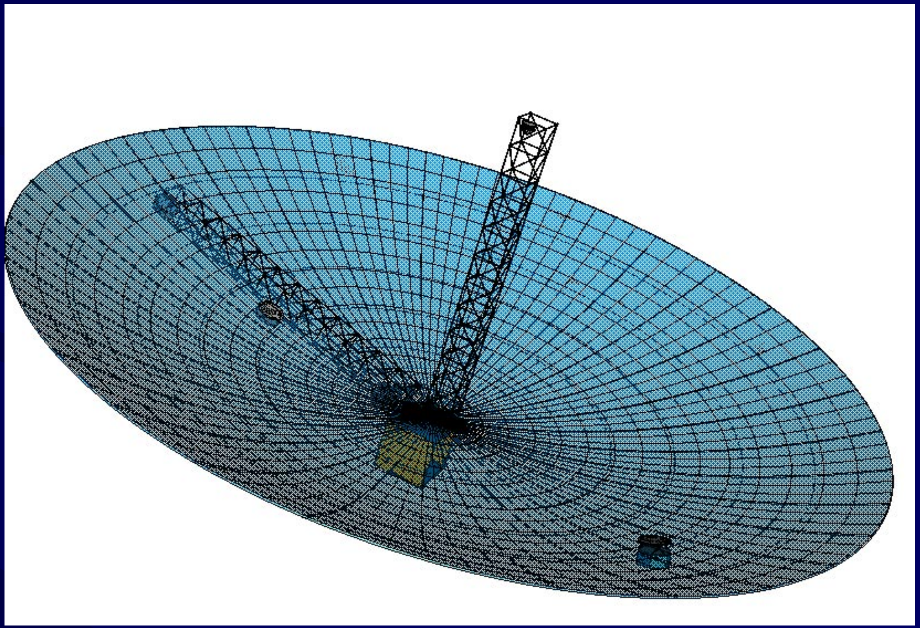
– possible within the current decade
– uses booms and/or a modest number of free-flying spacecraft
– operates with modest baselines
– performs beam combination with ultraviolet light
– produces UV images via imaging interferometry

- Such a mission with a small # of spacecraft
  – would require frequent reconfigurations and limit observations to targets whose variability does not preclude long integrations
  – would test most of the technologies needed for the full-size array

“Strawman” Pathfinder Design

- combination system using both a boom and a free-flyer
  - 3 sections of a parabola on a boom, with an attached mast to hold secondary mirror
  - 1 free-flyer with a deformable spherical secondary mirror, whose surface can be adjusted based on its location on the virtual mirror surface

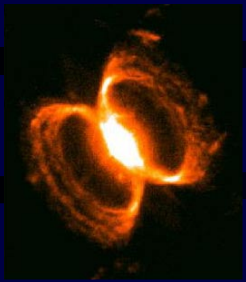




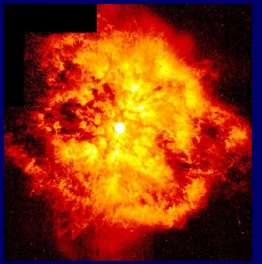
Place in NASA/ESA Strategic Roadmaps

- ***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 ***Terrestrial Planet Finder***, and it may serve as a useful technological and operational pathfinder for ***Planet Imager***
  - … 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



SI and General Astrophysics



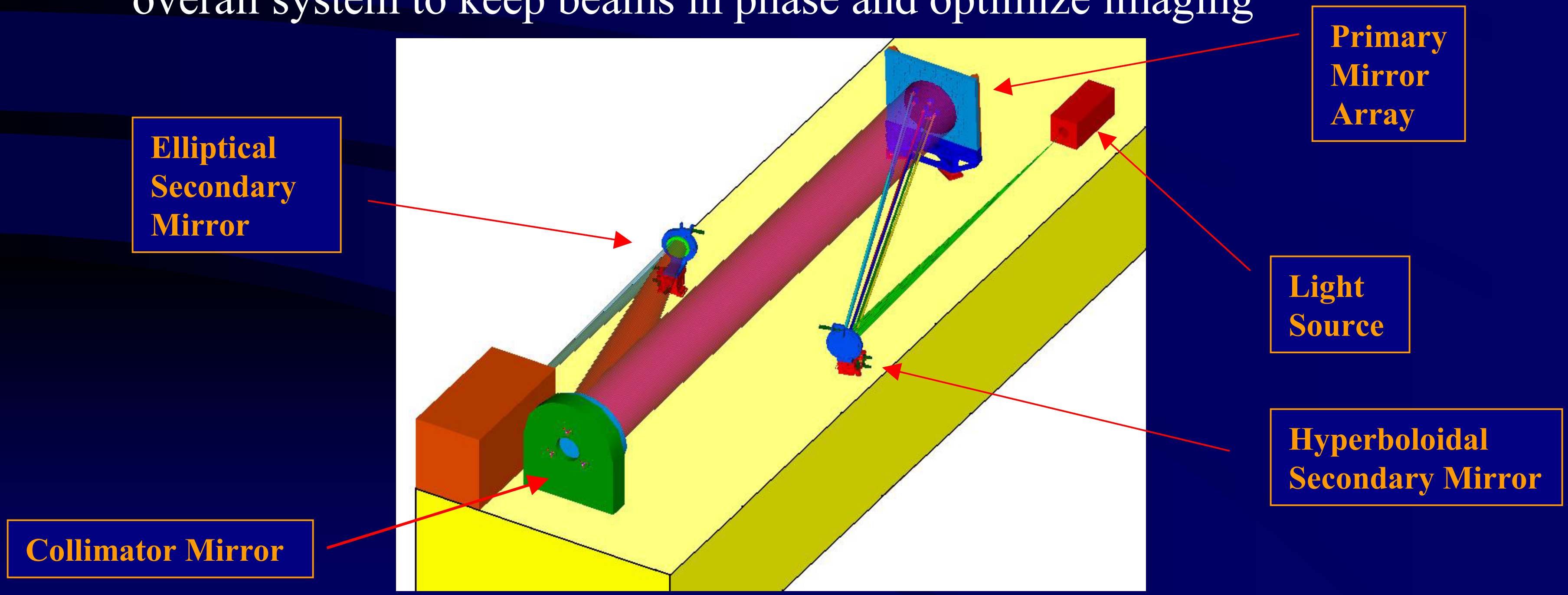
A long-baseline interferometer in space benefits many fields of astrophysics

Active Galactic Nuclei
transition zone between BLR & NLR,
origin/orientation of jets
Quasi-stellar Objects & Black Holes
close-in structure,
radiation from accretion processes
Supernovae
close-in spatial structure
Stellar interiors
internal structure in stars outside
solar parameters
Hot Stars
hot polar winds, non-radial pulsations,
envelopes and shells of Be-stars

Spectroscopic binary stars
observe companions & orbits,
determine stellar properties,
perform key tests of stellar evolution
Interacting Binary Stars
resolve mass-exchange, dynamical
evolution/accretion,
study more efficient dynamos
Forming Stars/Disk systems: accretion
foot-points & magnetic field structure
Cool, Evolved Giant & Supergiant Stars, and Long-Period/Semi-Regular Variables
spatiotemporal structure of extended
atmospheres/winds, shocks

The Fizeau Interferometer Testbed (FIT)

- A ground-based lab testbed at GSFC for UV-Optical Fizeau Interferometers
  - Designed to explore the principles of and requirements for the SI mission concept and other Fizeau Interferometers
  - Utilizes 7-30 separate apertures (each with 5 degrees of freedom: tip, tilt, piston, 2D translation of array elements) in a sparse distribution
  - Goal of demonstrating closed-loop control of articulated mirrors and the overall system to keep beams in phase and optimize imaging



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, CfA
- Recent Events
  - Requirements defined, optical design completed, hardware procurements in progress for Laboratory Fizeau Interferometry Testbed (FIT) at GSFC
  - IMDC Studies performed for full and Pathfinder missions
  - 3 supporting ISAL studies performed
  - full-color brochure published, "whitepaper" submitted to Roadmap panels
- Next Steps
  - Continue Architecture Trade/Feasibility Studies
  - Test/demonstrate design concepts with ground-based testbed (the FIT)
  - Gather & utilize additional community input
  - Produce book summarizing science/societal motivations for mission, technology roadmap, and most promising architecture options

For more information, see: **http://hires.gsfc.nasa.gov/~si**