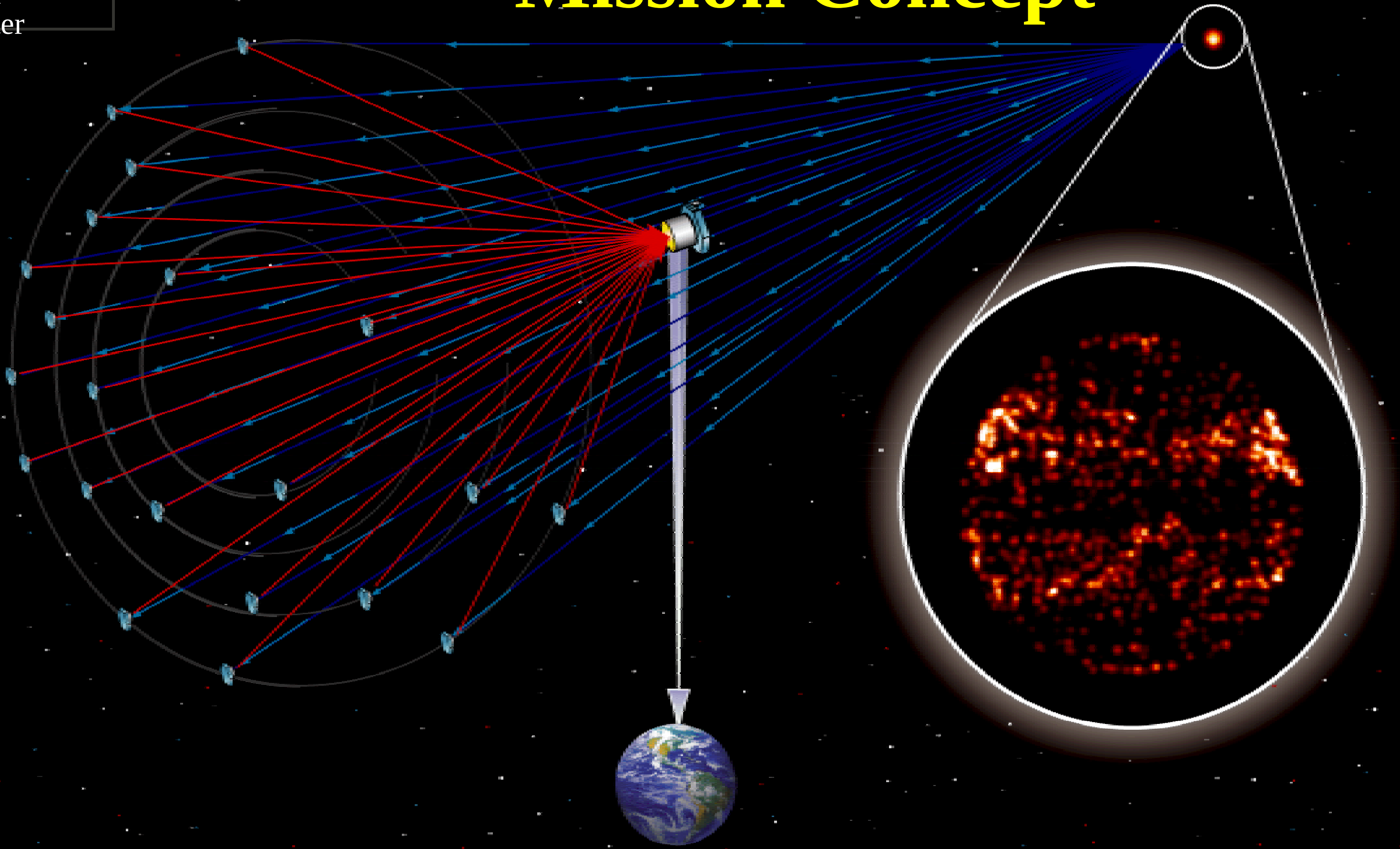
Goddard Space
Flight Center

Imaging the Surfaces and Interiors of Other Stars: The *Stellar Imager* (*SI*) Mission Concept



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Cool Stars 12: 2001 July 30-Aug 3

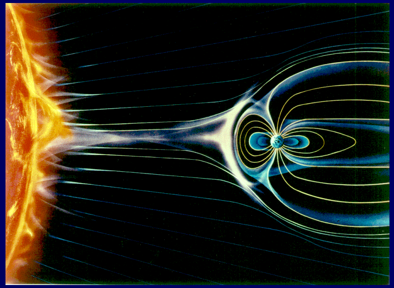
Primary Science Goals

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

Science 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

Problem:

there is no comprehensive model of solar/stellar magnetic activity!

Science Requirements

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

Primary Performance Goals

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

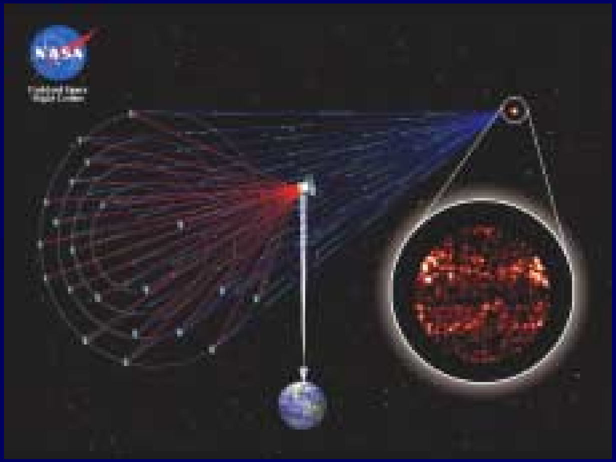
Design Requirements

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

Strawman Mission Concept (I)

The current leading architecture concept for Stellar Imager (SI) is that of a 0.5 km diameter space-based UV-optical Fizeau Interferometer composed of a reconfigurable array of 10 - 30 one-meter-class (spherical or flat) array elements on microsats. Those elements direct light to an image-plane beam combination facility in a hub at the prime or secondary focus. It will provide:

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



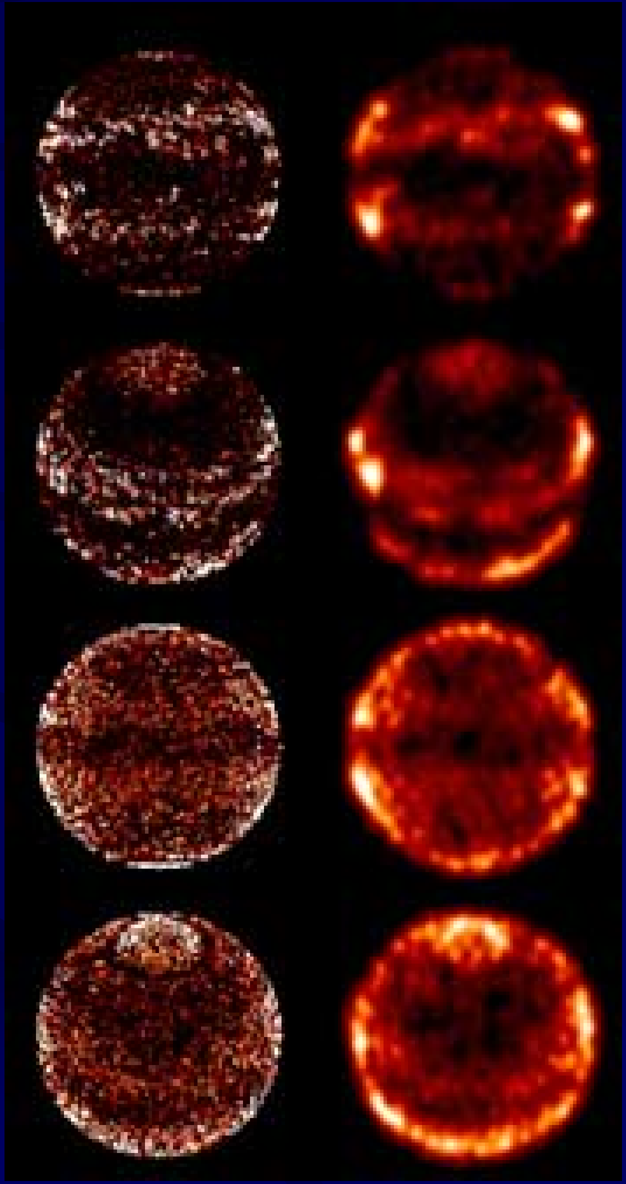
Strawman Mission Concept (II)

- SI will be located in Lissajous orbit around the sun-earth L2 point
  - cannot be in low-earth orbit because strong gravity gradient would not permit precise formation flying (potential scattered light problem as well)
  - earth-trailing orbit not desirable since replacement of failed array elements and addition of improved (larger) array elements would not be possible
  - L2 has both a small and very well characterized gravity gradient (permits precise formation flying) and should be accessible in 2015 time frame for servicing and upgrade by robotic and/or manned missions
- overall design: why Fizeau over Michelson?
  - tremendously simplifies the beam-combination station and thus substantially lowers the cost of using many array elements; the use of many array elements:
    - enables quick acquisition of data to support imaging of transient stellar surface features (intrinsic variations + rotational blurring) and high-time resolution asteroseismology
    - minimizes number of re-configurations of array needed to obtain number of baselines required to attain desired image quality (# baselines ~ #pixels). The benefits are:
      - low consumption of propellant enables desired long-duration mission
      - overhead time for reconfigurations minimized, observing efficiency and ability to image time-dependent phenomena maximized
  - minimizes number of reflections: critical to maintain UV sensitivity

Simulated Stellar Images (I)

Sample simulated CIV (1550 A) images of Sun-sized stars (left) and interferometric images (right) of those stars.

The interferometric images are computed using the SISIM code developed by two of the authors (R.A. and J.R.) for 12 elements in Y formation, moved in 15 degrees steps, with 200 CLEAN interations, and assuming a distance to the star of 4 pc and an array diameter of 250 meters.



← sun-like star
equator view

← sun-like star
40 deg latitude

← 30x solar activity
from equator

← 30x solar activity
40 deg latitude

Simulated Stellar Images (II)

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

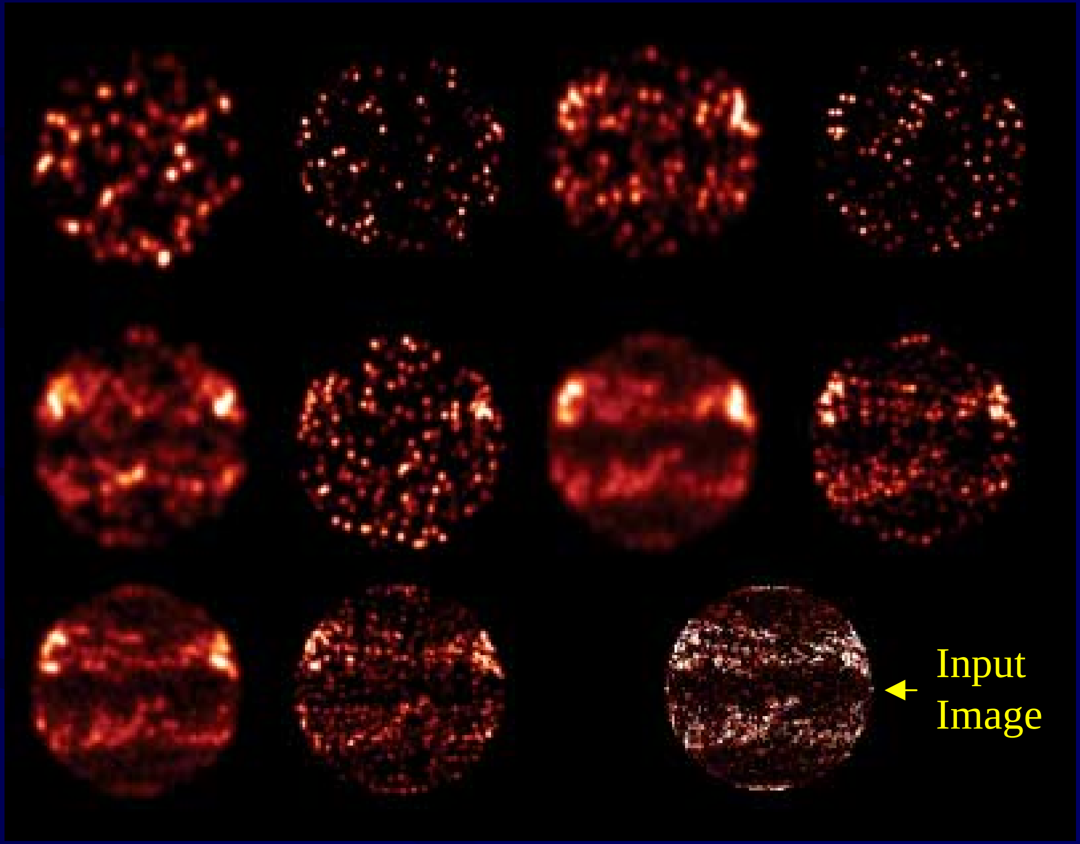
rotations(step size): 0 (0) 24 (15deg)

elements

6

12

30

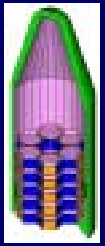


Baselines: 250 m 500 m 250 m 500 m

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

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

Results from Initial GSFC Integrated Mission Design Center (IMDC) Study (I)



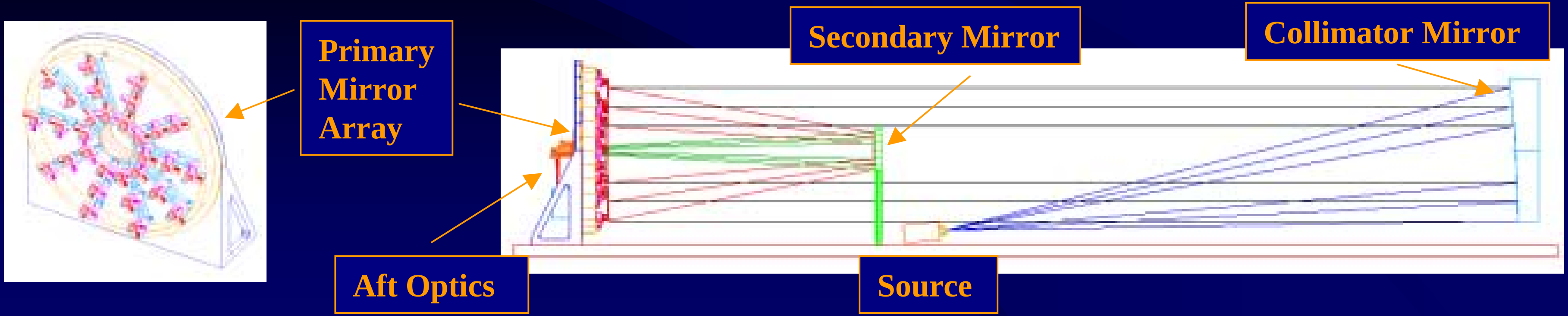
- Baseline concept studied by IMDC
  - 30 “mirrorsats” formation flying with beam-combining hub
  - control satellites to 5 nm, rather than use optical delay lines for fine tuning
  - Fizeau interferometer: 0.5 km max. baseline, 4 km focal length
- launch requirements not prohibitive
  - 3 good options: 3 Delta III, 1 Atlas V, or 2 Delta (III/IV) launches
  - preferred: dual launch of Delta IV 4450-14 (mirrorsats & dispenser) + Delta III 3940-11 (hub) allows for 30 134-kg mirrorsats + one 2600 kg hub
- power requirements
  - can be handled by existing solar cells, but must be *body-mounted* to avoid unacceptable impact on precision formation-flying and station-keeping
  - battery life/storage a concern
- propellant requirements at L2 modest
  - Field Emission Electric Propulsion (FEEP) can generate continuous, variable micro-Newton thrust for required 10 year lifetime on < 1 kg of solid fuel
- operations concept straightforward, assumes:
  - autonomous control of array station-keeping, reconfiguration, and slewing
  - ground interaction only for command uploads and anomaly resolution
- thermal design: main concern is keeping mirrors isothermal

IMDC Results (II)

- communications requirements
  - normal: mirrorsats talk to hub and each other, hub talks to earth
  - contingency operations: mirrorsats can be commanded directly from earth
  - desired enhancement: central communcations hub at L2 for all missions
- precision metrology and formation-flying
  - the “tallest poles” among numerous technical challenges
  - 3-level approach envisioned
    - rough formation control via radio frequency (RF) ranging and thrusters (to m’s)
    - intermediate control (to cm’s) via modulated laser ranging
    - fine control (to nm’s) via feedback from science data system/phase diversity
- long mission lifetime requirement second biggest concern
  - hub will have redundant components, but need to seriously consider building backup hub for launch-on-need or original deployment
  - need to fly additional backup mirrorsats to put into operating array as original set suffers expected failures (mirrorsats are low-redundancy)
- most important “enabling technologies” needing further study/development
  - Deployment/initial positioning of elements in large formations, Metrology/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)

Ground-based Laboratory Testbeds at GSFC for UV-Optical Fizeau Interferometers/Sparse Aperture Telescopes

- the Phase Diverse Testbed (PDT) - nearing completion
  - utilizes a masked filled-aperture to simulate a system with 3 moving apertures
  - enables testing of Phase Diversity algorithms which will allow the determination of optical wavefront needed to drive control systems to maintain adequate phasing for high-resolution imaging from an array of formation-flying spacecraft
- the Fizeau Interferometry Testbed (FIT): in design/development (shown below)
  - designed to explore the principles of and requirements for the Stellar Imager mission concept and other Fizeau Interferometers/Sparse Aperture Telescope missions
  - utilizes a large number of truly separate, articulated apertures (each with 5 degrees of freedom: tip, tilt, piston, 2D translation of array elements) in a sparse distribution
  - has the long-term goal of demonstrating closed-loop control of articulated mirrors and the overall system to keep beams in phase and optimize imaging
  - enables critical assessment of various image reconstruction algorithms (phase diversity, clean, MEM, etc.) for utility and accuracy by application to real data



Primary Mirror Array

Secondary Mirror

Collimator Mirror

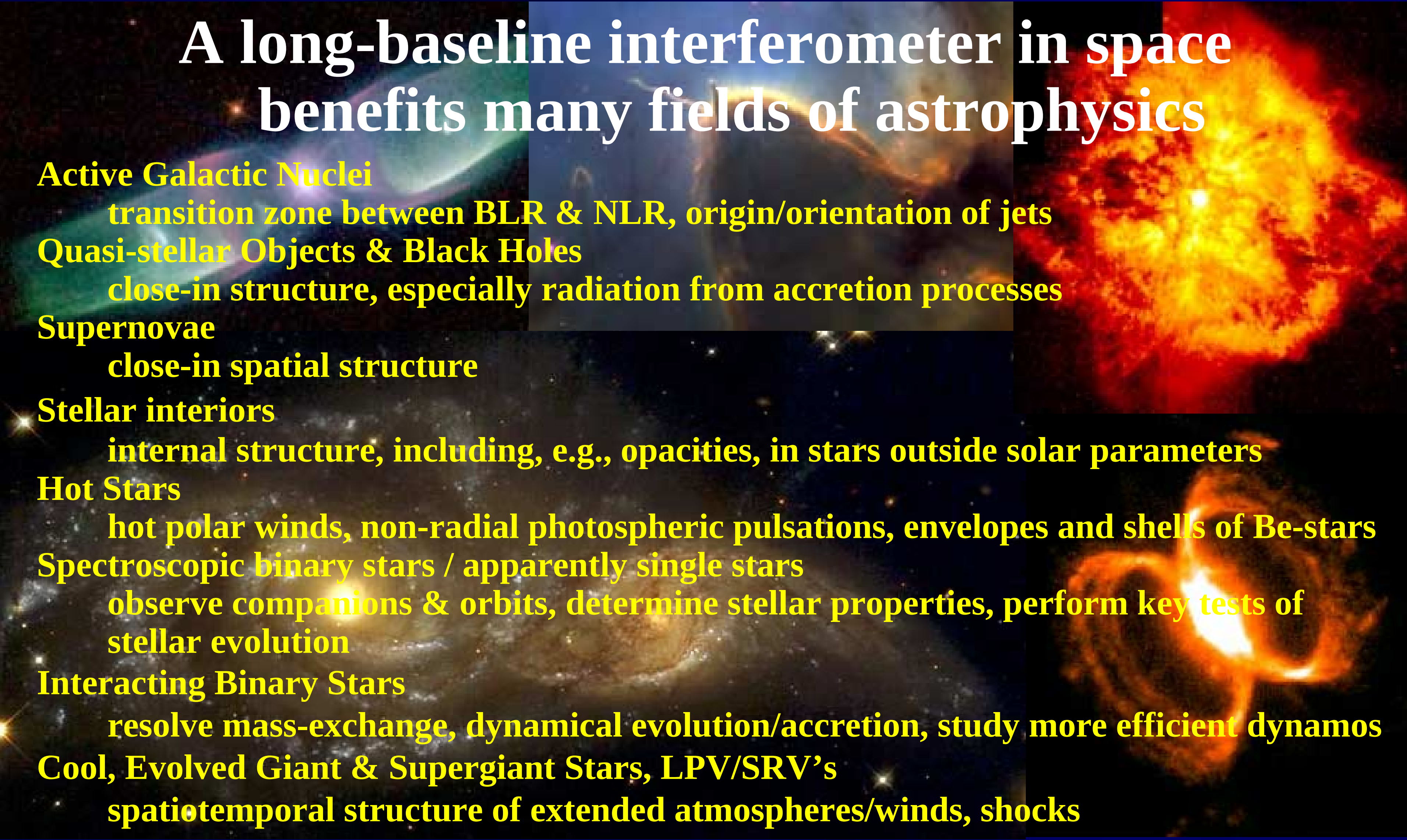
Aft Optics

Source

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 the ***Planet Imager****:* ***SI*** resolution is ~40x less demanding than ultimate NASA goal
  - … while addressing science goals of 3 NASA/OSS research Themes
    - understand why the sun varies (SEC)
    - understand the origin of stars, planetary systems, and life (Origins)
    - understand the structure and evolution of stars (SEU)
  - it is complementary to the planetary imaging interferometers
    - ***Terrestrial Planet Finder***, ***IRSI/Darwin***, and ***Planet Imager*** null the stellar light to find and image planets
    - ***Stellar Imager*** images the central star to study the effects of that star on the habitability of planets and the formation of life on them.
    - ***TPF, SI, IRSI/Darwin,*** and ***PI*** together provide complete views of other solar systems

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, especially radiation from accretion processes
- Supernovae
  - close-in spatial structure
- Stellar interiors
  - internal structure, including, e.g., opacities, in stars outside solar parameters
- Hot Stars
  - hot polar winds, non-radial photospheric pulsations, envelopes and shells of Be-stars
- Spectroscopic binary stars / apparently single stars
  - observe companions & orbits, determine stellar properties, perform key tests of stellar evolution
- Interacting Binary Stars
  - resolve mass-exchange, dynamical evolution/accretion, study more efficient dynamos
- Cool, Evolved Giant & Supergiant Stars, LPV/SRV’s
  - spatiotemporal structure of extended atmospheres/winds, shocks

Current Status

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