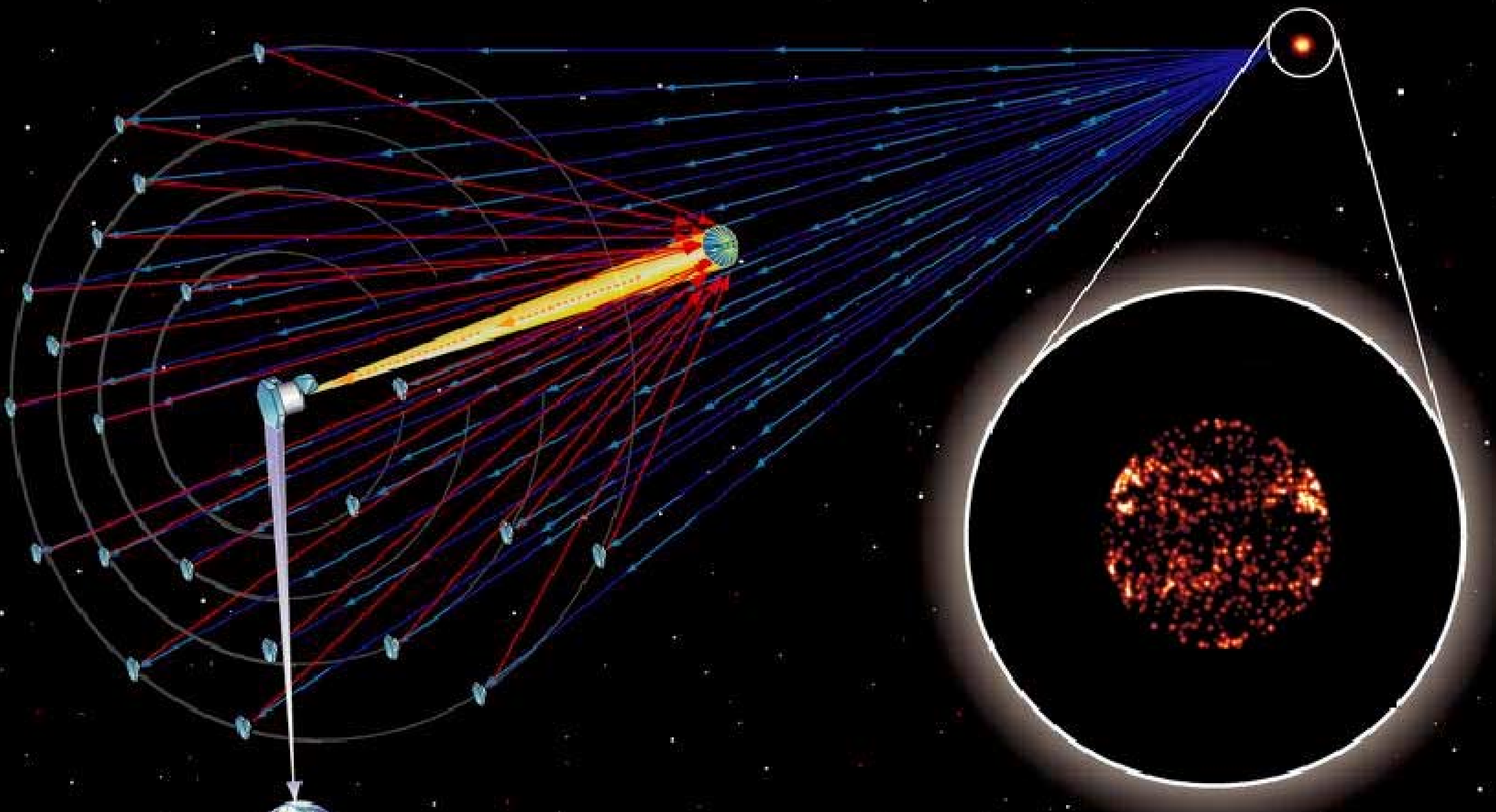
Goddard SFC

The *Stellar Imager* (*SI*) Mission Concept



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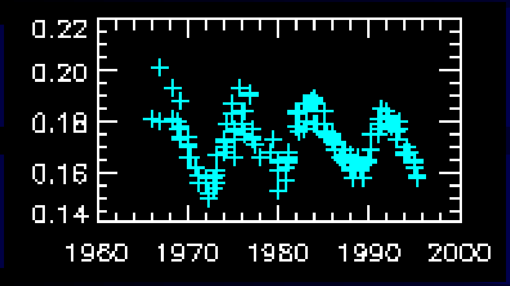
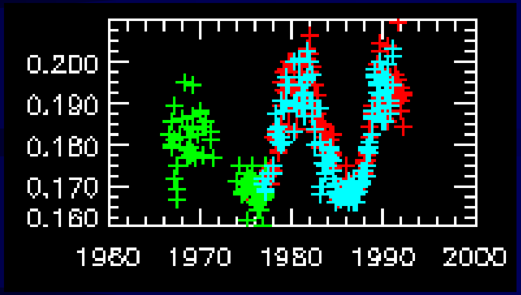
Primary Science Goals

- 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

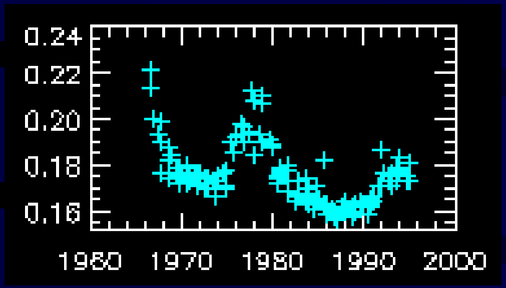
Manifestations of Magnetic Activity



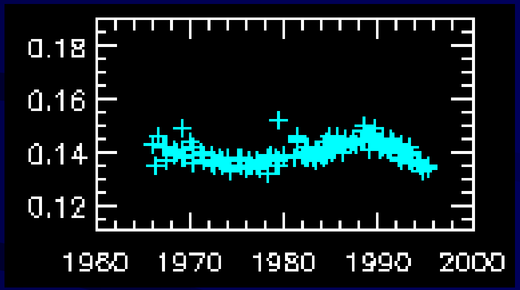
HD 81809: 8.2 yrs



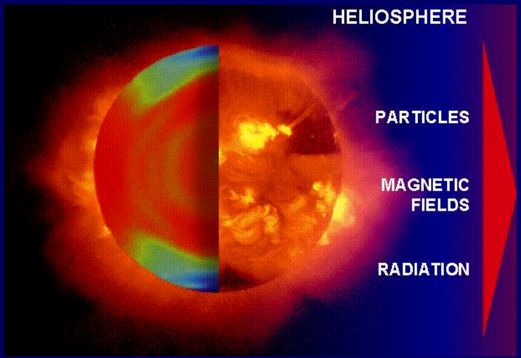
The Sun: 11 yrs

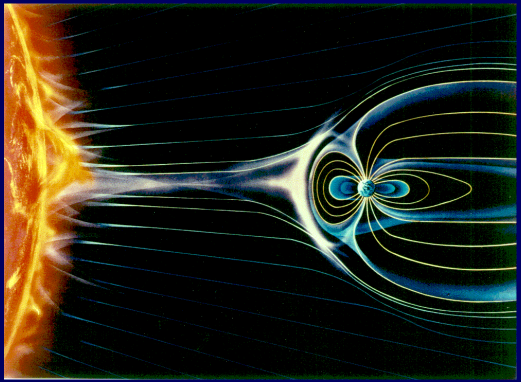


HD 3651: 13.8 yrs



HD 136202: 23 yrs



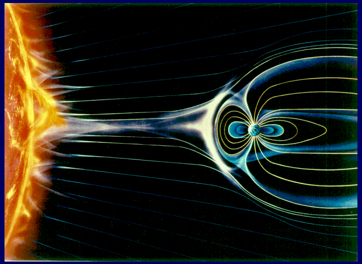


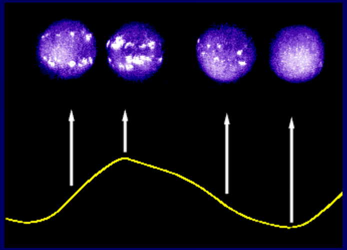
- stellar luminosities show cyclic changes (e.g. Mt. Wilson Ca II disk-integrated flux)
- long-term solar variations have induced climate changes on Earth, such as the 17th-Century Little Ice Age during the Maunder (low-activity) minimum

- In solar/stellar atmospheres:
  - magnetic regions & star spots;
  - very hot outer atmospheres;
  - explosive flares & high-energy particles and radiation;
  - stellar wind & coronal mass ejections

Value to Society: Space-Weather & Earth-Climate Forecasting

- We must develop & validate a dynamo model in order to
  - understand past solar activity
  - enable forecasting of solar and heliospheric activity days to decades in advance
  - anticipate the impact of those changes on the earth's biosphere and society from
    - long-term changes which effect climate, such as Maunder minima and grand maxima, can lower/raise overall global temperatures and cause crop failures
    - short-term changes, e.g. enhanced activity/flares, have the potential to
      - disable communication satellites
      - knock out power grids
      - increase the speed of corrosion of oil pipelines
      - place astronauts at risk from particle radiation





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

- Image different stars of different activity
  - 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)
  - 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
- Enable asteroseismology, using low to intermediate degree non-radial modes to measure internal stellar structure & rotation

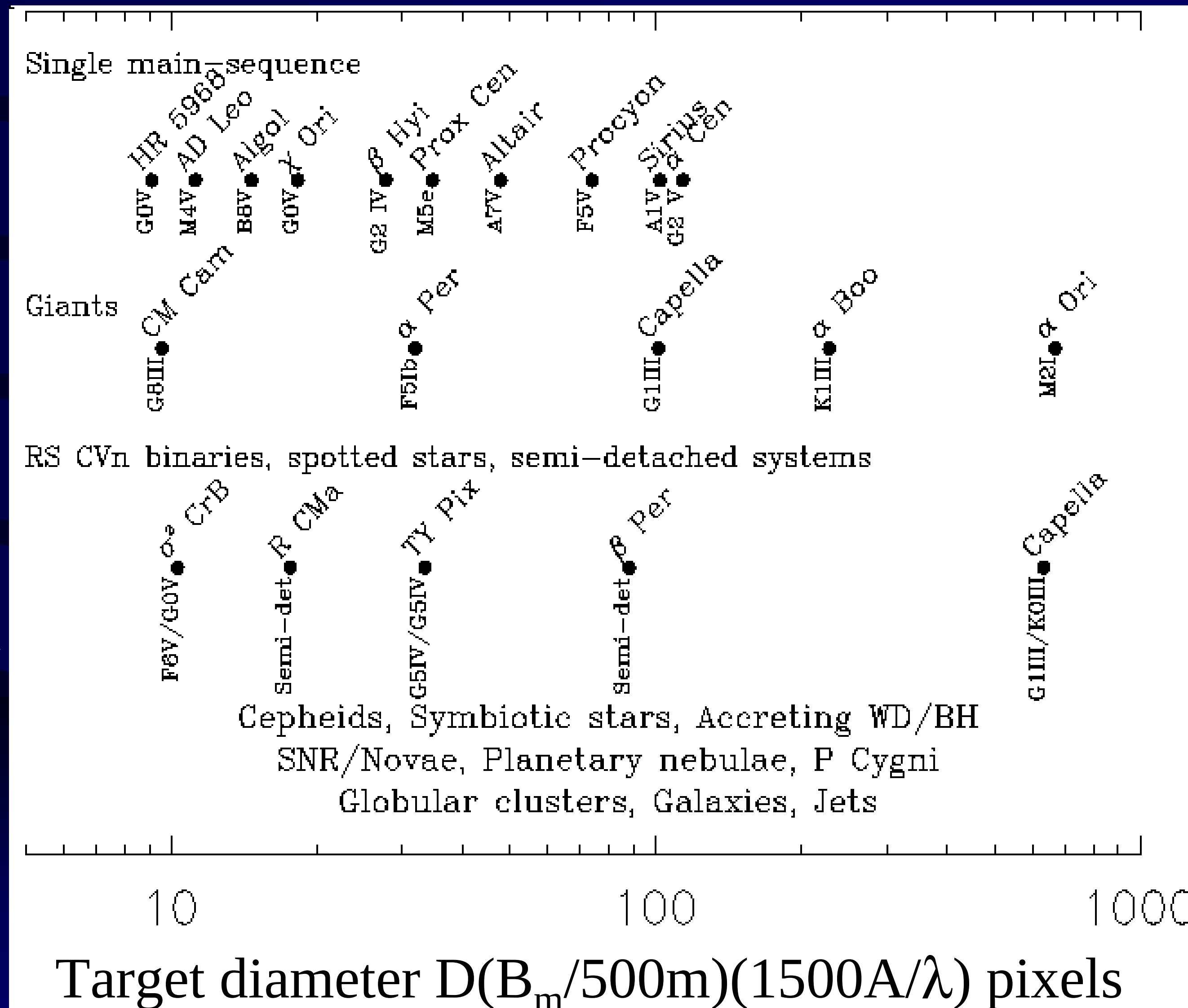
Design Requirements

- 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
    - high-contrast bright spots are 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, making them the ideal activity diagnostics
  - modest integration times (~ hours for dwarfs to days for giants) to avoid smearing of images due to rotation & activity evolution
- 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

Sample Targets

Sample target categories:

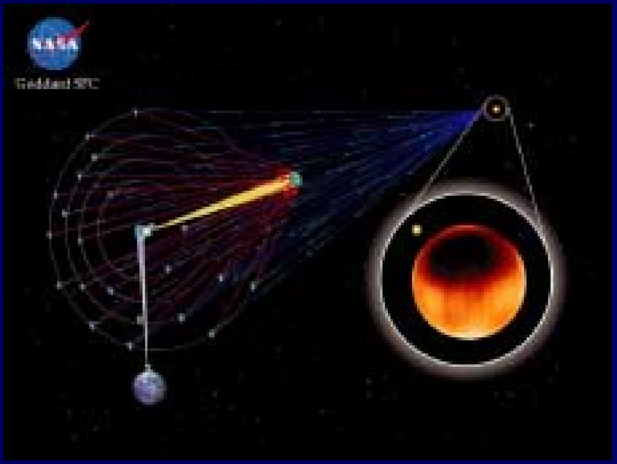
χ Ori	"Young Sun"
β Hyi, α Cen	Solar analogs
HR 5968	Maunder-minimum star
α Boo	"Ancient Sun"
Altair, Procyon, α Per	Onset activity
AD Leo, Prox Cen	Flare star; deep convection
CM Cam	Giant polar spot
Capella , σ CrB	Magnetically interact. binary
TY Pyx	Compact binary
R CMa, β Per	Semi-detached binary
α Ori	Supergiant star
Algol	Mass transfer
Sirius	Hot star



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 (> 5-10 year) mission to study stellar activity/magnetic cycles:
  - individual telescopes/central hub can be refurbished or replaced as needed



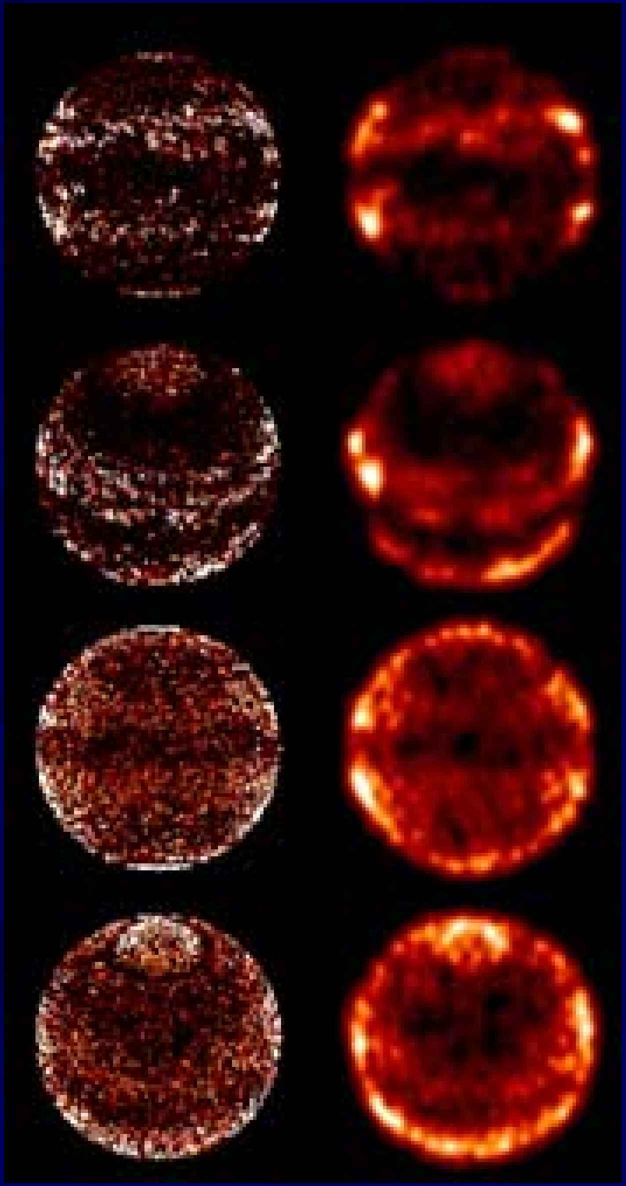
Strawman Mission Concept (II)

- SI will be located in a halo 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

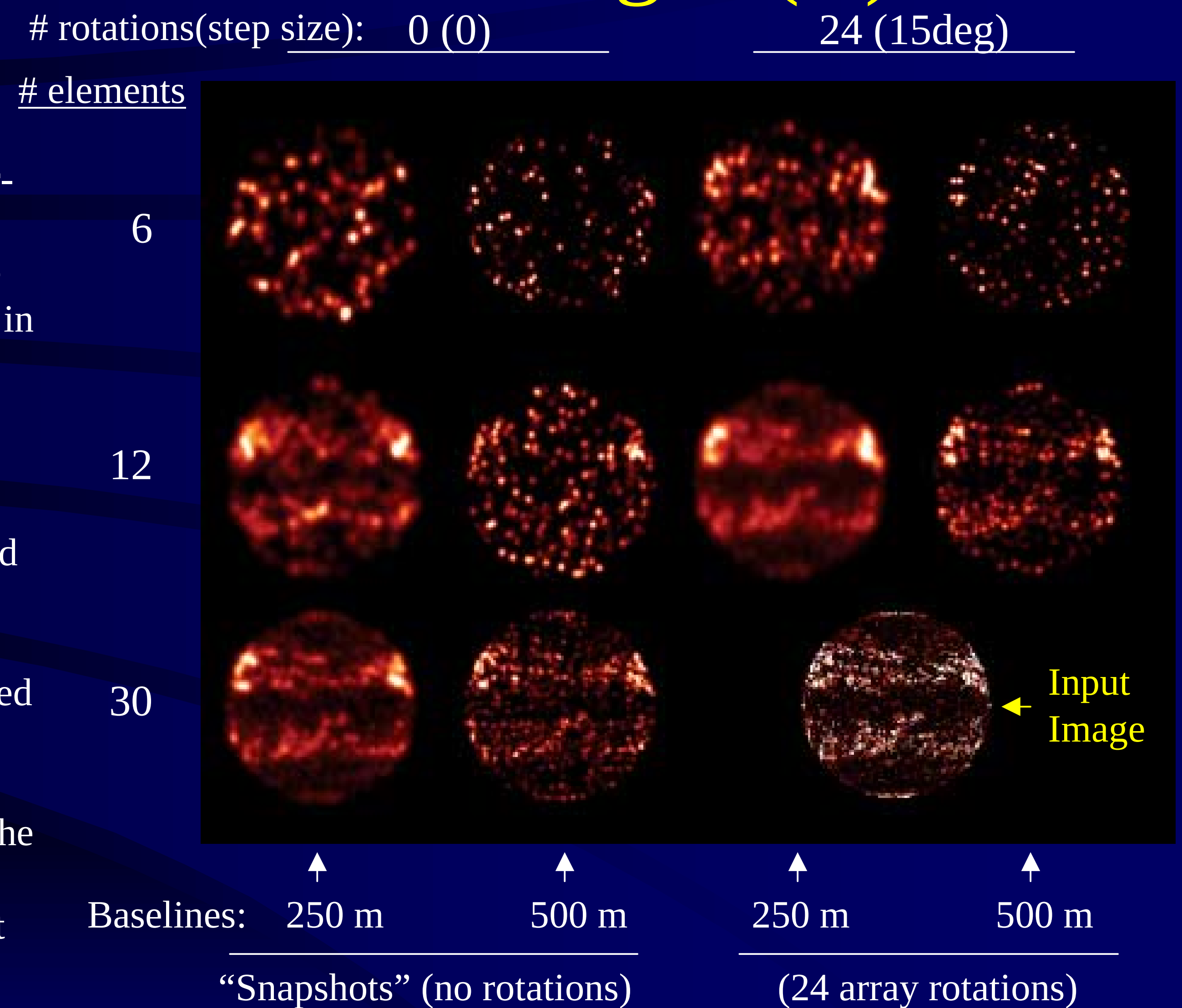
← sun-like star 40 deg latitude

← 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.



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).

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
- Requirements defined for
  - Laboratory Fizeau Interferometry Testbed (FIT) at GSFC
  - GSFC Integrated Mission Design Center (IMDC) Study
- Next Steps
  - Perform 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