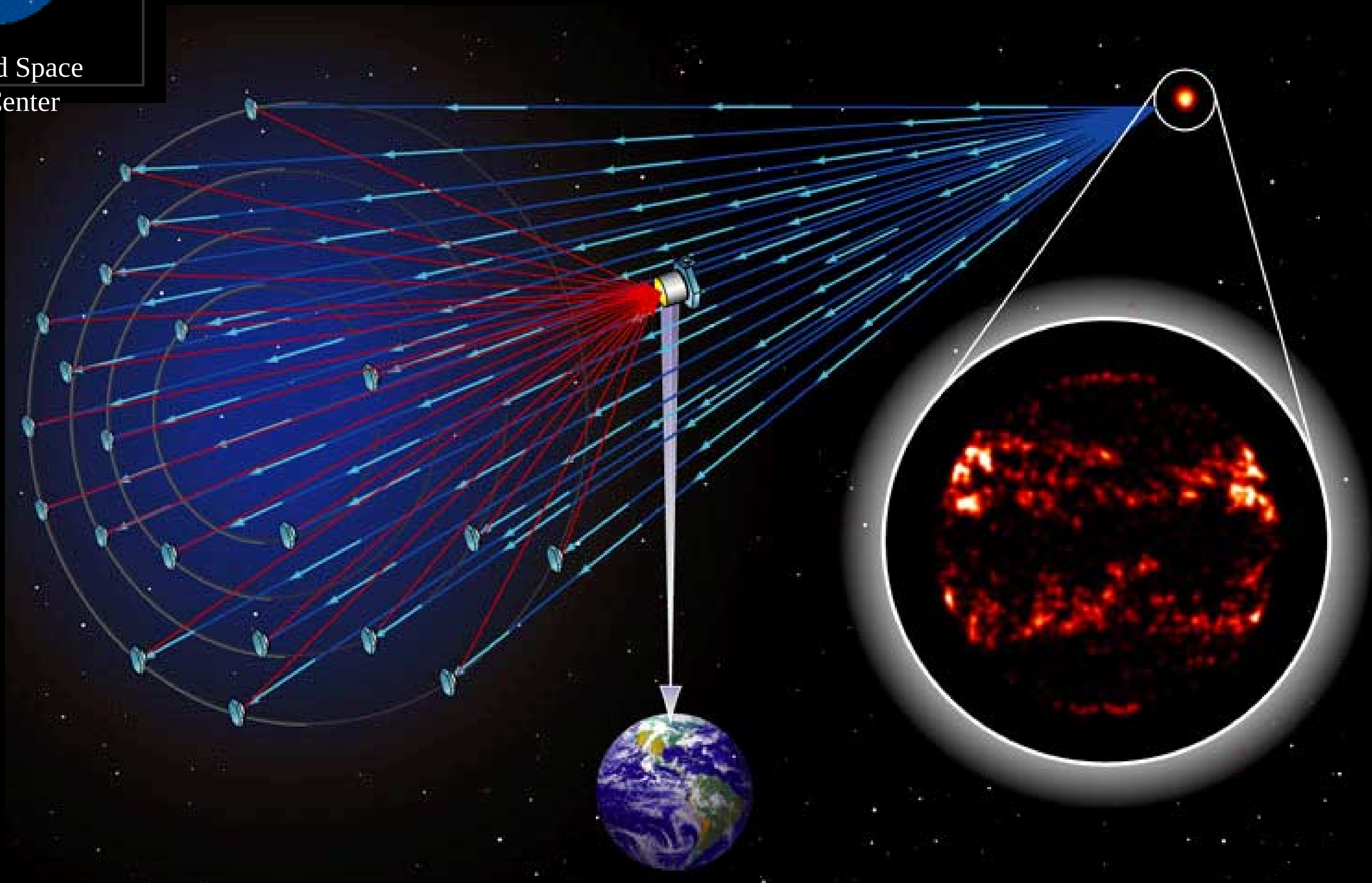
Goddard Space
Flight Center

Stellar Imager (SI)



Kenneth G. Carpenter (NASA/GSFC)
Carolus J. Schrijver (LMATC)

*CfA, Cambridge, MA:
2002 March 26*

Mission Concept Development Team

- Mission concept under development by NASA/GSFC in collaboration with LMATC, NRL/NPOI, STScI, UMD...
  - NASA-GSFC: Ken Carpenter (Study Lead), Rick Lyon (Testbed Lead), Joe Marzouk/Sigma, Greg Solyar/UMBC, Xiaolei Zhang/SSAI, Lisa Mazzuca, Bill Danchi, Susan Neff
  - LMMS/ATC: Carolus Schrijver (Science Lead)
  - NRL/NPOI: Tom Armstrong, Dave Mozurkewich, Tom Pauls
  - STScI: Ron Allen, Jay Rajagopal
  - UMD: Lee Mundy
- consultants
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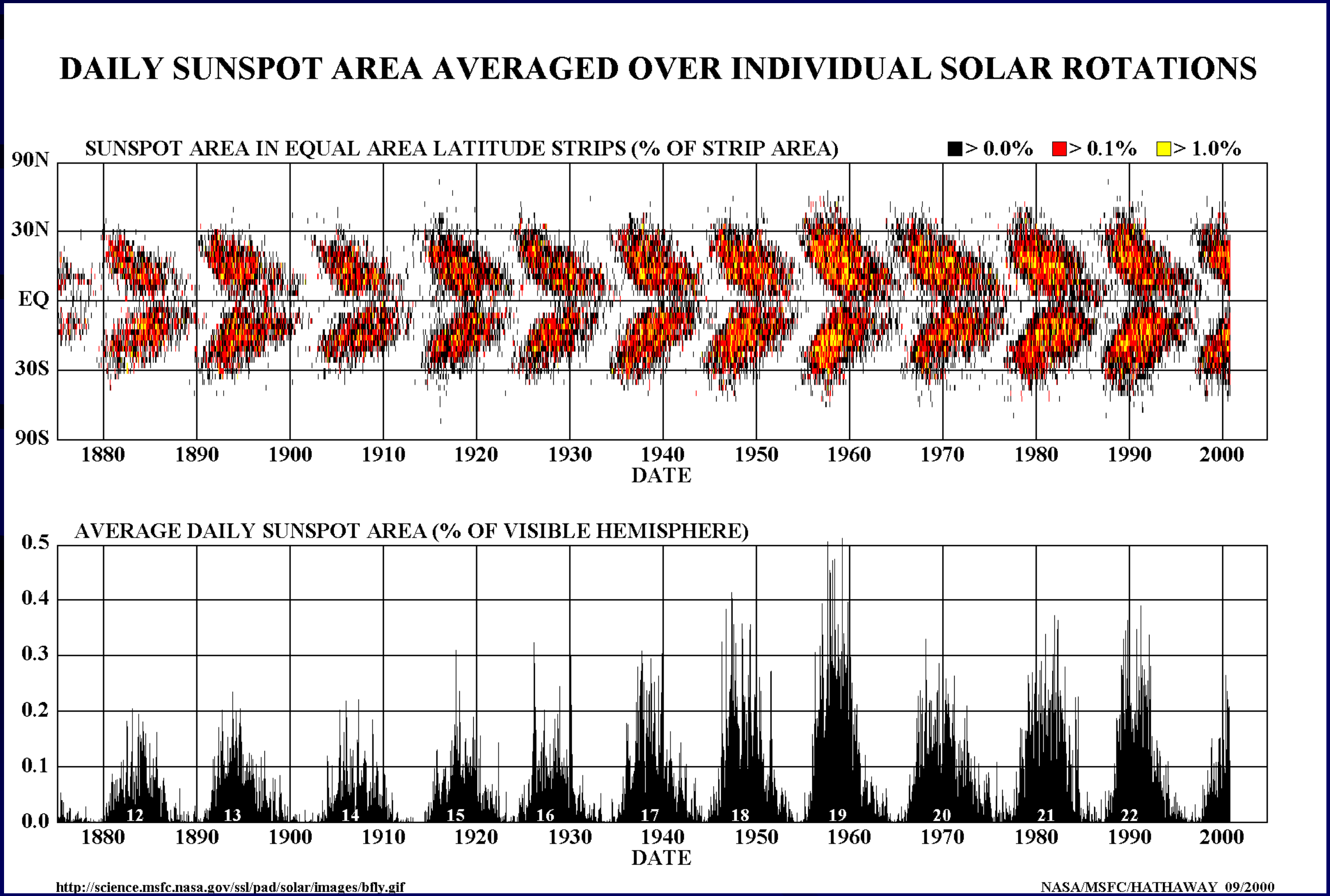
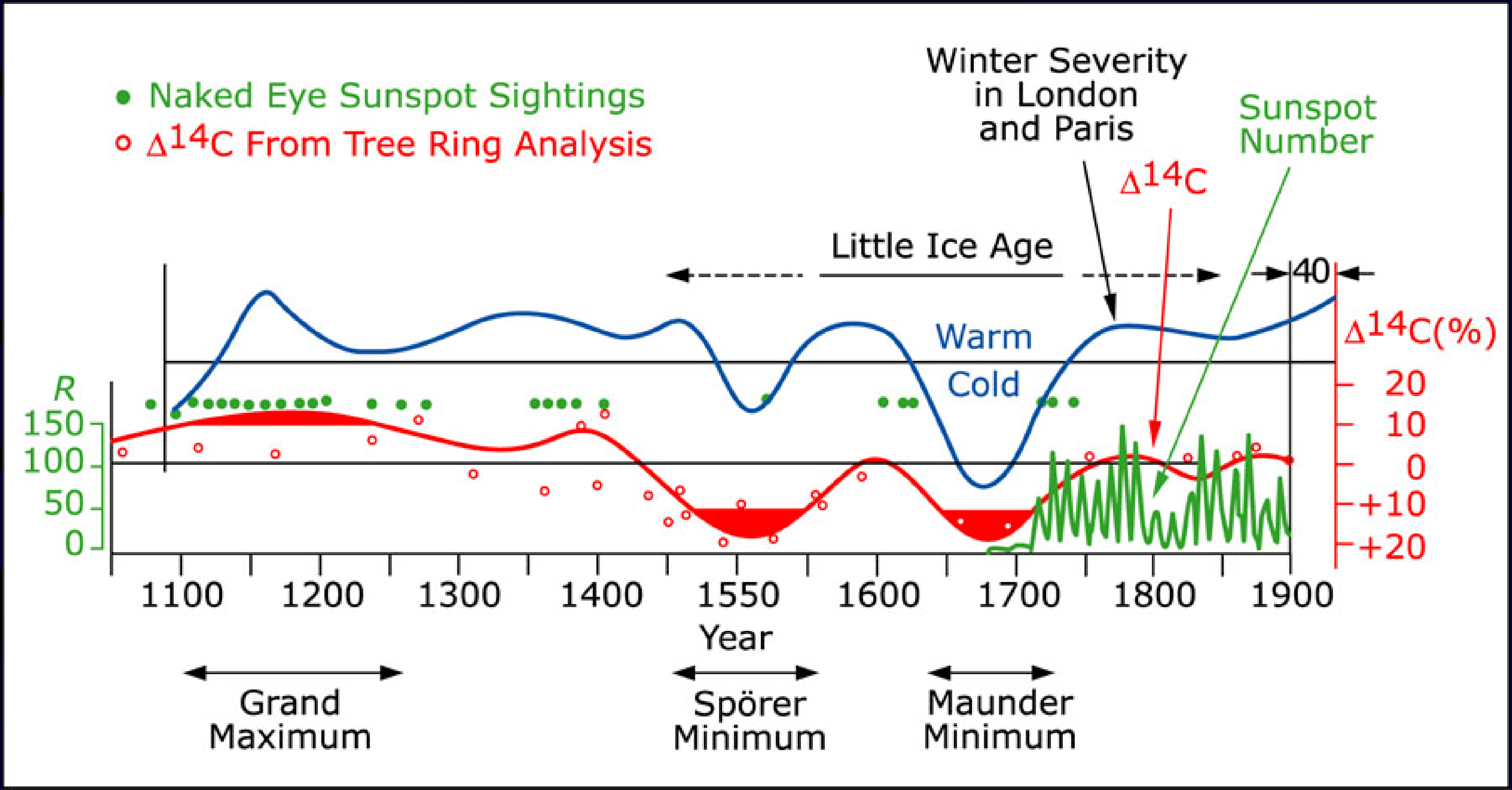
Science Context: The Importance of Understanding Stars and Stellar Dynamos

- The Sun is only one of many classes of stars, but our close-up view of the Sun has enabled discoveries that have revolutionized physics and astrophysics time and again
  - existence of helium, role of nuclear fusion, convective envelopes, interior structure by acoustic sounding, neutrino deficit
  - importance of non-linear, non-local processes (radiation, 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 topology and induces associated activity which makes stars (including the sun) ever-changing and “dynamic”. That 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 its effect on planetary climate through variations it induces in luminosity, wind, and radiation
- Understanding stars and the dynamo process in general is the foundation for understanding the Universe

Spatial/Temporal Patterns of Solar Activity: The Butterfly Diagram & #spots vs. time



Solar Variations Since AD 1000



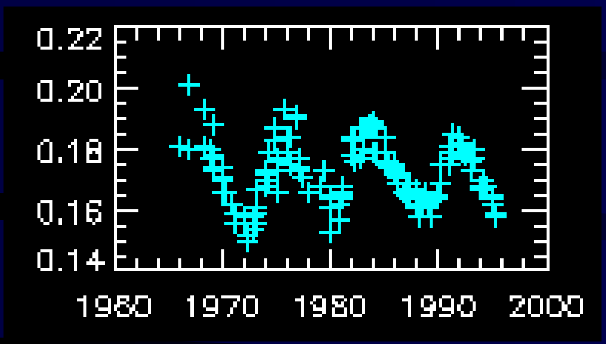
Current Impacts of Solar Activity on Earth (I)

- Long-timescale changes
  - Maunder Minimum (1645-1715)
    - total luminosity change of ~ 0.3 %
    - UV spectrum may have changed by a few % near 2500 A and by > 40% near 1200 A
    - thought to have triggered Little Ice Age in 17-th Century
      - crops failed in Northern Europe
      - people skating on the Thames River in London in June
  - Solar Grand Maximum in late Middle Ages
    - produced peak in earth temperatures
    - such peaks can aggravate human-produced greenhouse effects and increase global warming
    - current increasing global temperatures likely due to both increasing solar activity and greenhouse gases, which dominates is disputed

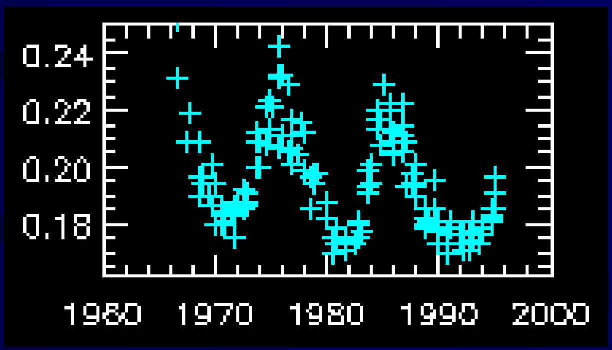
Current Impacts of Solar Activity on Earth (II)

- Short-timescale changes
  - solar wind induces aurorae at high earth latitudes
  - enhanced episodes (electrical storms)/flares have
    - disabled communication satellites
    - knocked out power grids
    - increased the speed of corrosion of oil pipelines
    - placed astronauts at risk from particle radiation
- Current state of the sun
  - level of solar activity has been steadily increasing since Maunder Minimum
  - peak of Modern Maximum forecast for early in the 21st century

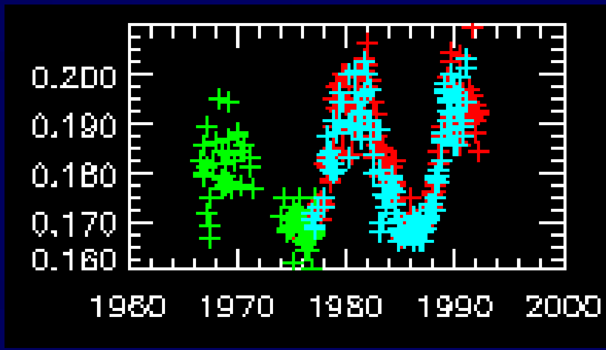
Temporal Patterns of Stellar Activity I.: Disk-Integrated Ca II Light (Mt. Wilson Program)



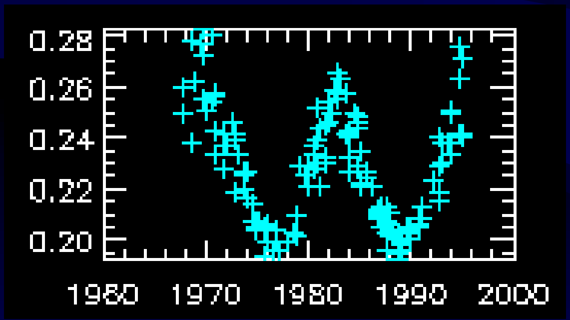
HD 81809: 8.2 yrs



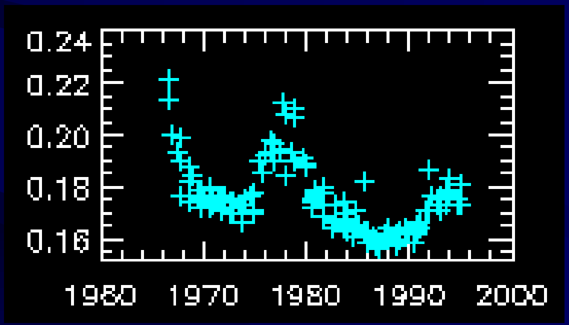
HD 10476: 9.6 yrs



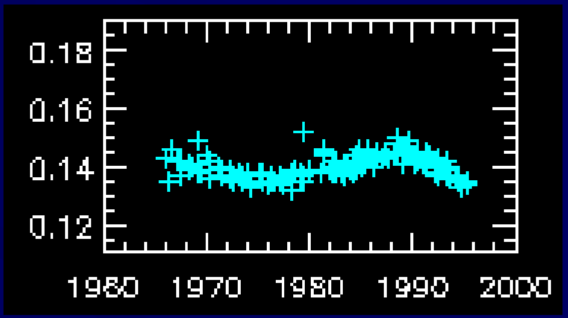
The Sun: 10 yrs



HD 16160: 13.2 yrs



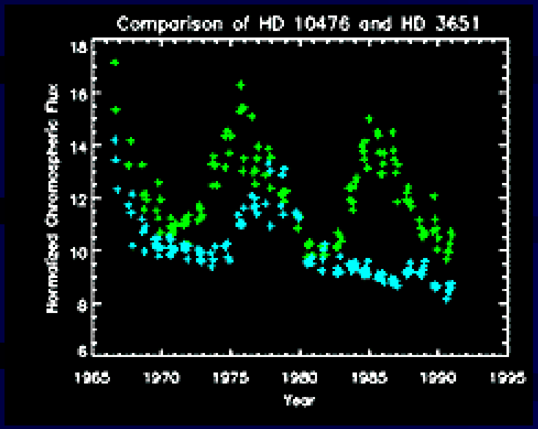
HD 3651: 13.8 yrs



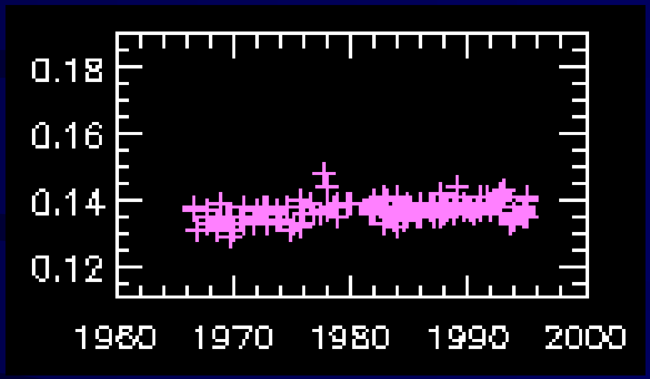
HD 136202: 23 yrs

Ref.: Baliunas et al.: www.mtwilson.edu

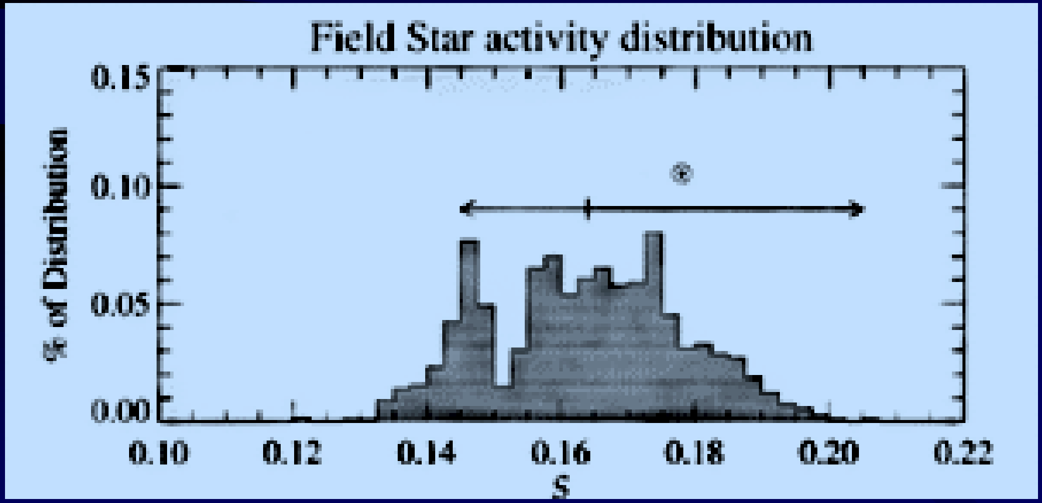
Temporal Patterns of Stellar Activity II: Ca II “Maunder-Minimum” Stars (Mt. Wilson Prog.)

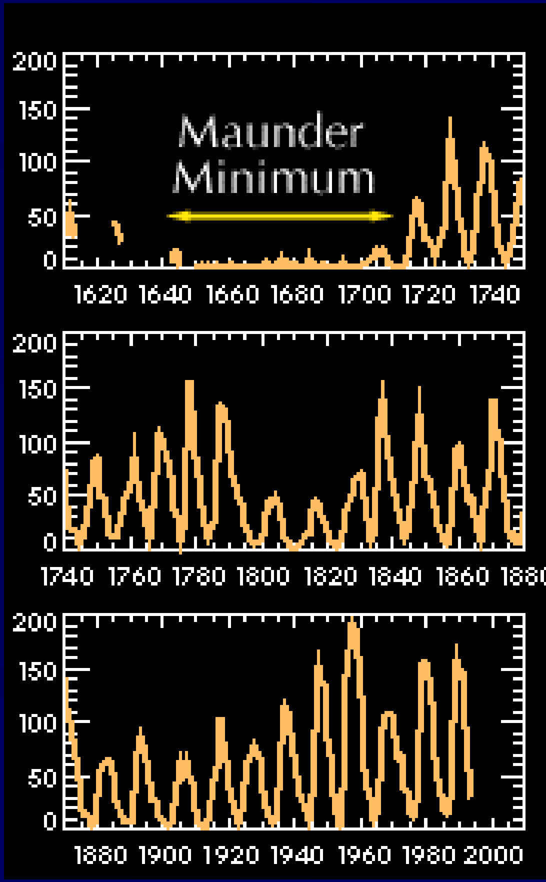


HD 10476 & 3651



HD 9562: mmin



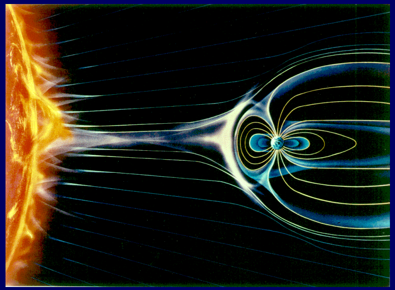


Ref.: Baliunas et al.: www.mtwilson.edu

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!

Furthering our Understanding of Solar/Stellar Magnetic Activity & its Effect on Life in the Universe: Introducing the *Stellar Imager (SI)*

- *SI* is a large space-based UV-optical interferometer designed for high angular resolution
  - zooms in on "point sources" so they turn into objects that can be imaged in detail, thereby opening up an entire new realm of science
  - reveals processes no one has seen before, thereby driving theoretical developments in a host of fields
  - provides a tool to astrophysicists of the same fundamental nature as the microscope to biologists

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

Additional Science Goals

- Obtain detailed imaging information on processes that affect the origin and evolution of stars, planets, and life
  - **study the origin of stars and planetary systems**
    - magnetic fields and star birth, coupling of star and disk, redistribution of angular momentum and the formation of planets
  - **study the origin and continued existence of life**
    - magnetic activity and the formation of complex organic molecules
    - quasi-cyclic magnetic variability and the habitability of biospheres
  - **study structure and evolution of stars**
    - asteroseismology impacts fundamental physics: nuclear reactions, mixing processes, composition gradient, opacities, neutrino oscillations, ….?
    - stellar mass loss
    - binary-star interaction

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

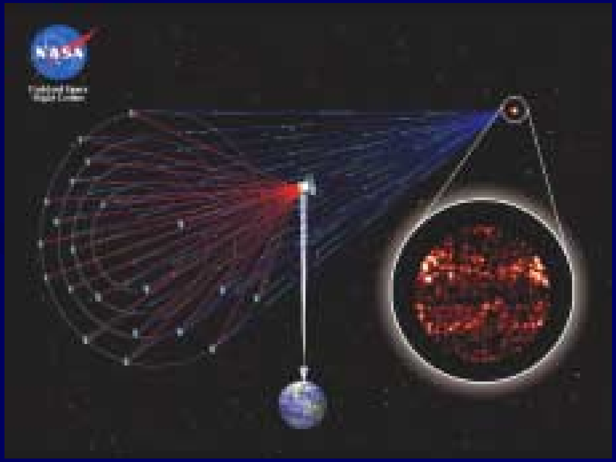
- Obtain surface images of stars with different activity levels
  - for a substantial sample of nearby dwarf and giant stars, obtain a resolution of order 1000 total pixels (33x33) (~50,000 km on a Sun-like star at 4 pc)
  - study a sample in detail, revisiting over many years
  - measure:
    - sizes, 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 Stellar Imager (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
- a reconfigurable array of 10-30 one-meter-class spherical mirrors
  - those "mirrorsats" direct light to an image-plane beam combination facility in a hub at the prime 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

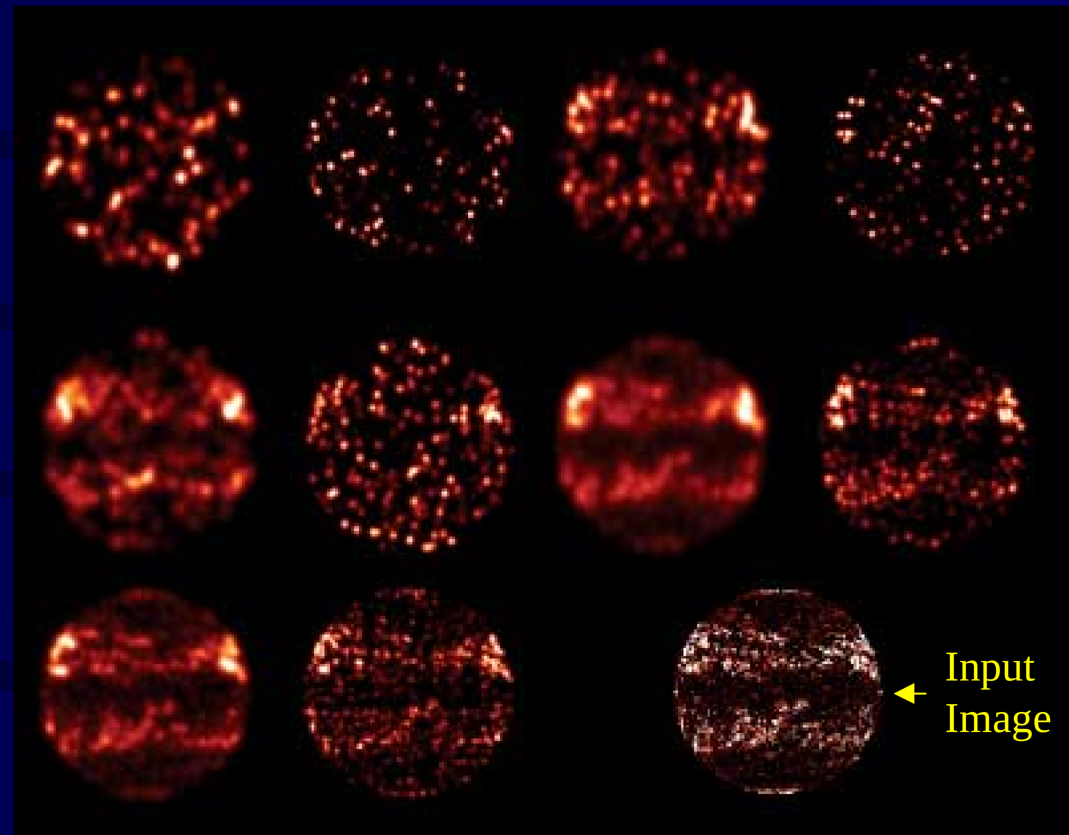


Strawman Mission Concept (con’t)

- SI location: 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

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 (Allen & Rajagopal, STScI) 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.

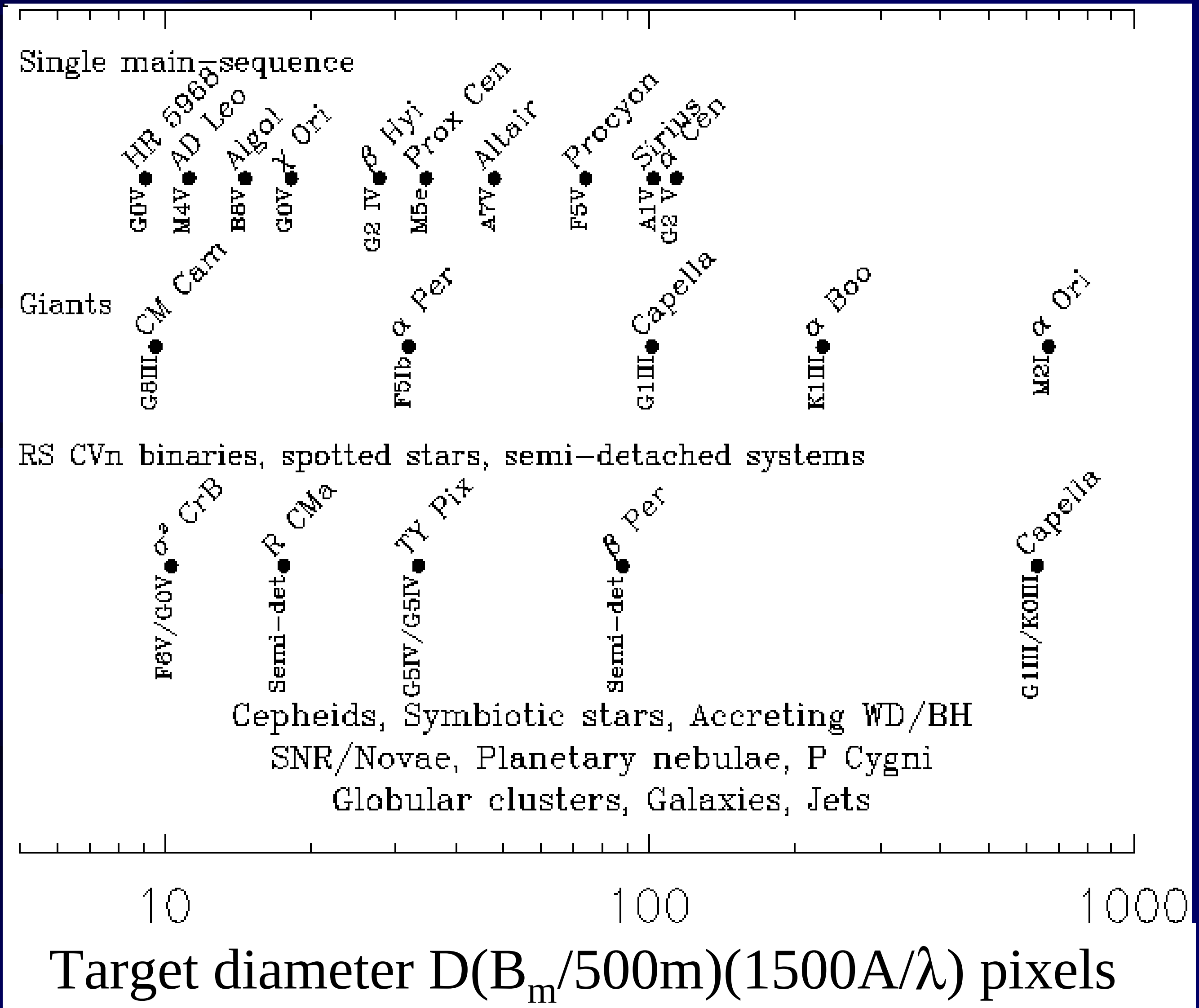


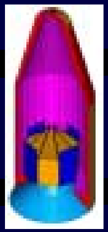
Conclusion: 30 static elements appear to be sufficient to adequately synthesize this stellar image, although 1 rotation of this array ought to improve things substantially still. Alternatively, fewer elements can be used with a larger number of rotations (6 elements/24 rotations or 12 e/6 r).

Sample Targets

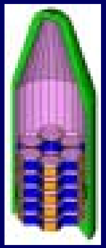
Sample target categories:

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





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
- station-keeping 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
- re-configuration and re-targeting thrusters will be separate system

IMDC Results (II)

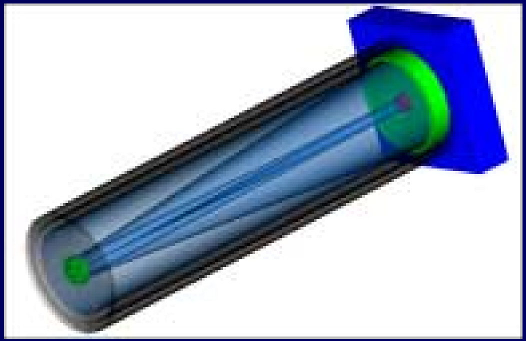
- operations concept straightforward, assumes:
  - autonomous control of array station-keeping, reconfiguration, and slewing
  - ground interaction only for command uploads and anomaly resolution
- thermal design: main concern is keeping mirrors isothermal
- communications requirements
  - normal: mirrorsats talk to hub and each other, hub talks to earth
  - contingency operations: mirrorsats can be commanded directly from earth
  - desired enhancement: central communications 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)

IMDC Results (III)

- most important "enabling technologies" needing further study/development
  - Deployment/initial positioning of elements in large formations
  - Metrology and autonomous nm-level control of many-element formations over kilometer scales
    - R. Laskin/JPL has technology initiative for metrology at this level
  - 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)

Instrument Synthesis Analysis Laboratory (ISAL) Studies

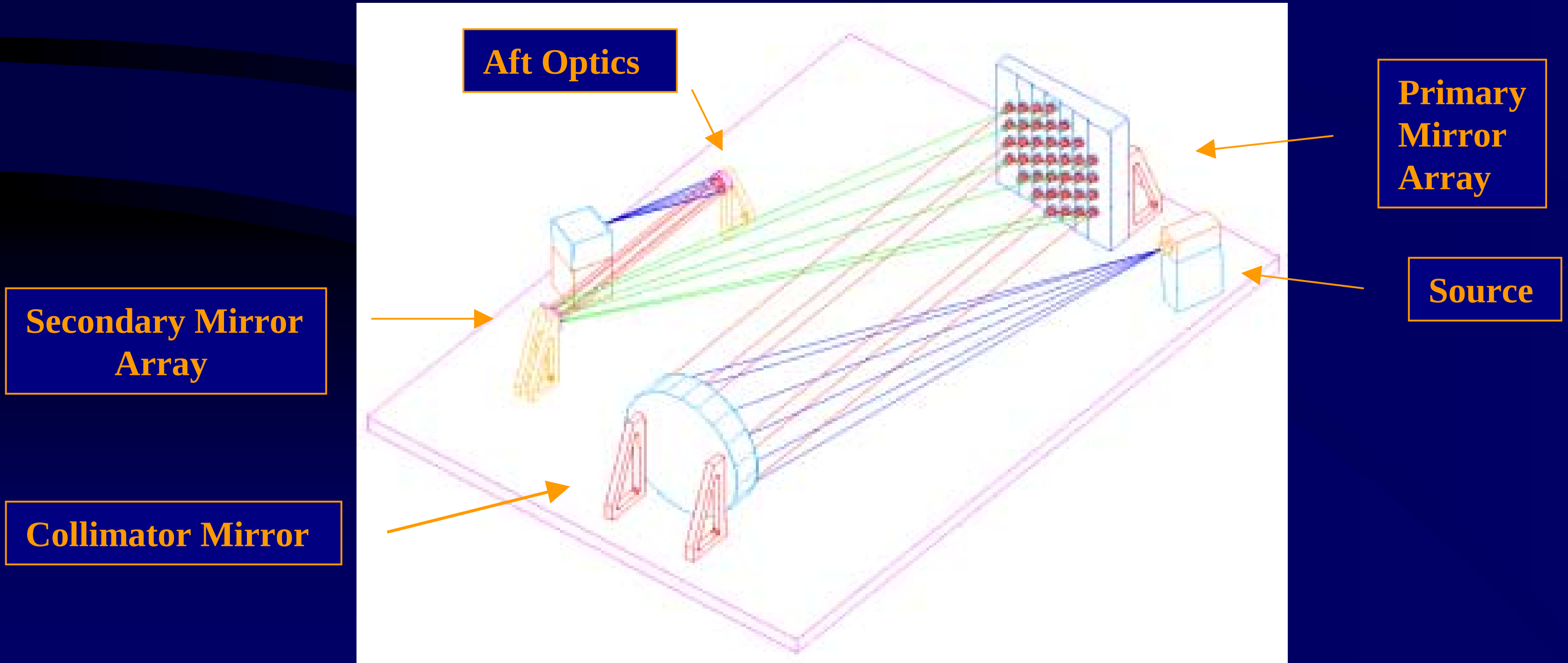
- "Super Star-Tracker"
  - investigating techniques for 30 micro-arcsec pointing control
  - Gravity Probe B - like system most promising
    - **Telescope on hub only centroids on beacons on "mirrorsats"**
    - **Gyro provides inertial reference frame**



- "Visual (CCD-LED, APS) formation sensor"
  - for course acquisition and positioning of "mirrorsats" relative to hub s/c
  - development of a sensor required for synthetic aperture formation initialization (6 DOF relative for each spacecraft) in low-gravity environments entirely outside of range of GPS. Concept has a star-tracker-like CCD or APS sensor on a mothership with a FOV large enough to just encompass the formation of daughter spacecraft. Each daughter spacecraft has 3 or more LED beacons. Concept is derived from VISNAV work that has been done by Texas A&M funded by Code R/CETDP.

The Fizeau Interferometer Testbed (FIT)

- A ground-based laboratory testbed at GSFC for UV-Optical Fizeau Interferometers / Sparse Aperture Telescopes
  - 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



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