A Dream of a Mission: Stellar Imager and Seismic Probe

A voyage of exploration to understand the stars, the formation of planetary systems, and the existence of life

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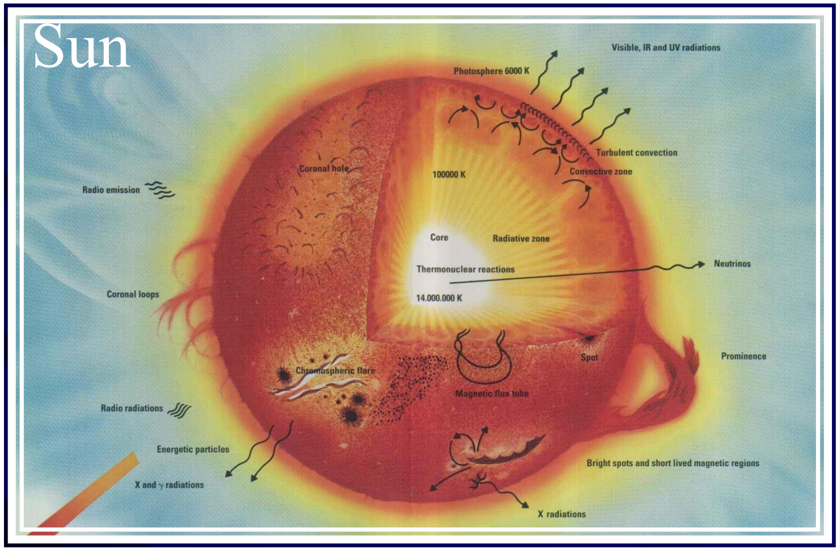
Of all the stars in the Universe only one has been seen as it truly is… highly complex and ever-changing



Imagine seeing other stars close up ...

Understanding Stars

- The Sun is only one of many classes of stars
- Our close-up view of the Sun led to discoveries that revolutionized physics and astrophysics time and again
  - stars are gaseous spheres; many have hot outer atmospheres
  - existence of helium, nuclear fusion, convective envelopes, interior structure by acoustic sounding, neutrino deficit
  - importance of non-linear, non-local processes (radiation, magnetic dynamo, convection, global circulation)
- Our comprehension of stars forms the foundation of our understanding of the Universe

Overview of the presentation

- NASA/OSS Science Priorities/Strategies
- Science goal within NASA/SEC quests:
  - Understand solar magnetic activity by imaging the surface and interior of stars
  - Forecast space weather and Earth climate
- Introducing the **S**tellar **I**mager and **S**eismic **P**robe
- Other SISP science goals for SEC, Origins, SEU
- Plans for SISP in the near future

NASA/OSS Science Priorities

Understand:

- (5) how stars and planetary systems form …
- (7) mechanisms of […] solar variability, …
- (9) the external forces […] that affect life and the habitability of Earth
- (11) how life may originate and persist beyond Earth

Goal 2: understand how stars and planetary systems form and determine whether life-sustaining planets exist around other stars in the solar neighborhood

Goal 3: understand how life originated on Earth and determine whether it began and may still exist elsewhere as well

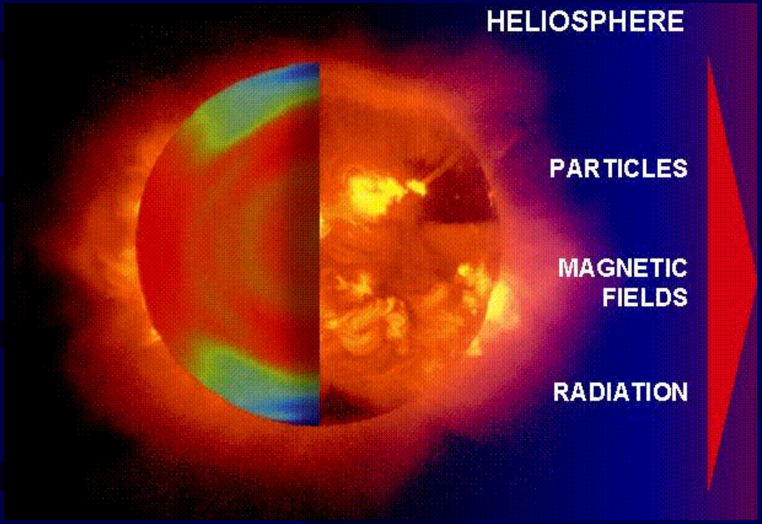
Quest 4: lives of stars; star birth, fusion, starlight and elements for life, explosions

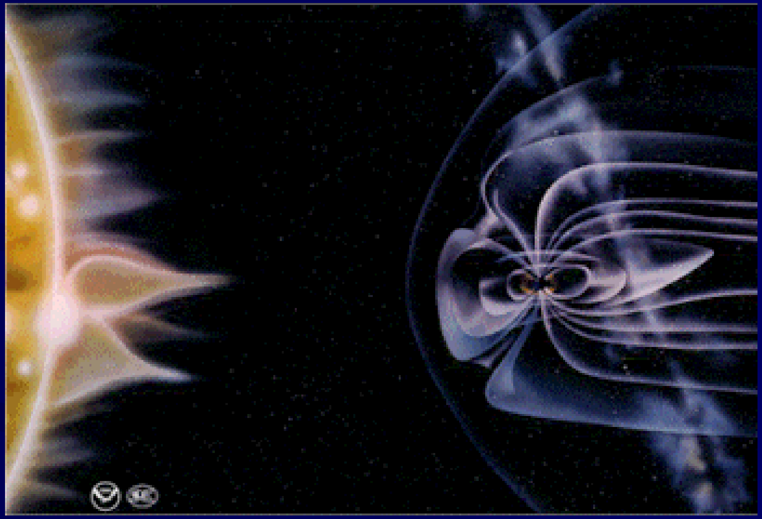
Quest 1: Why does the Sun vary?

NASA/OSS Strategic Science

- Origins/SEU/SEC year-2000 Road Maps call for a focus on
  - The formation of stars and planetary systems
  - The origin of life near stars
  - The evolution of stars
  - The effects of the central star on the habitability of the planetary biosphere
- All focus topics are related to stellar activity

Manifestations and Effects of Stellar Magnetic Activity





- Solar luminosity shows cyclic changes
  - induced climate changes on Earth, such as the 17th-Century Little Ice Age during the solar Maunder 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

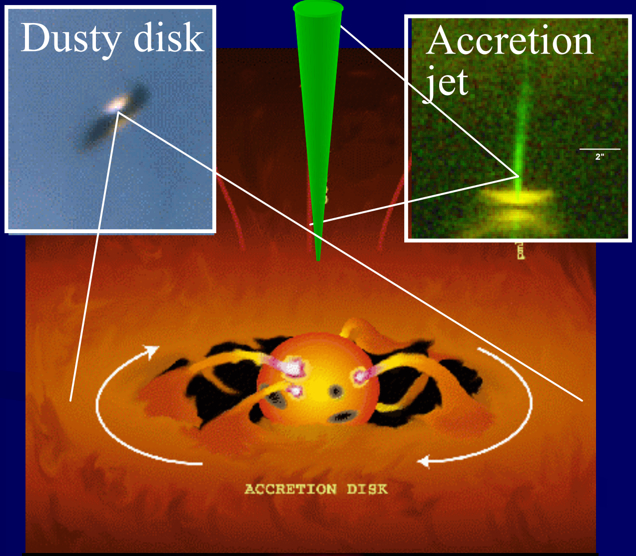
Life and Stellar Magnetic Activity

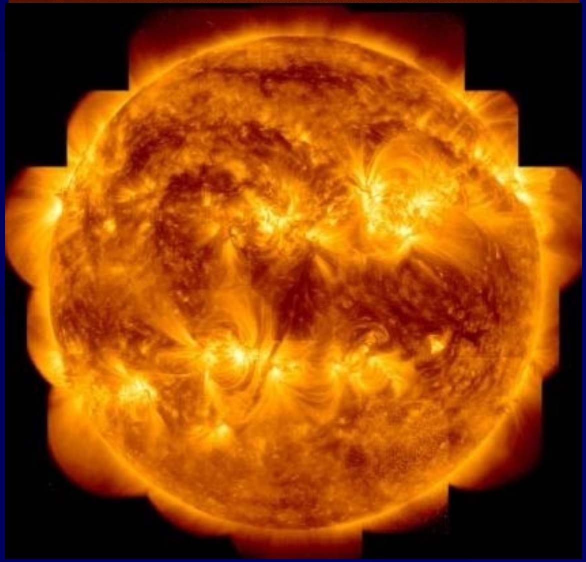
The stellar magnetic field

- 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

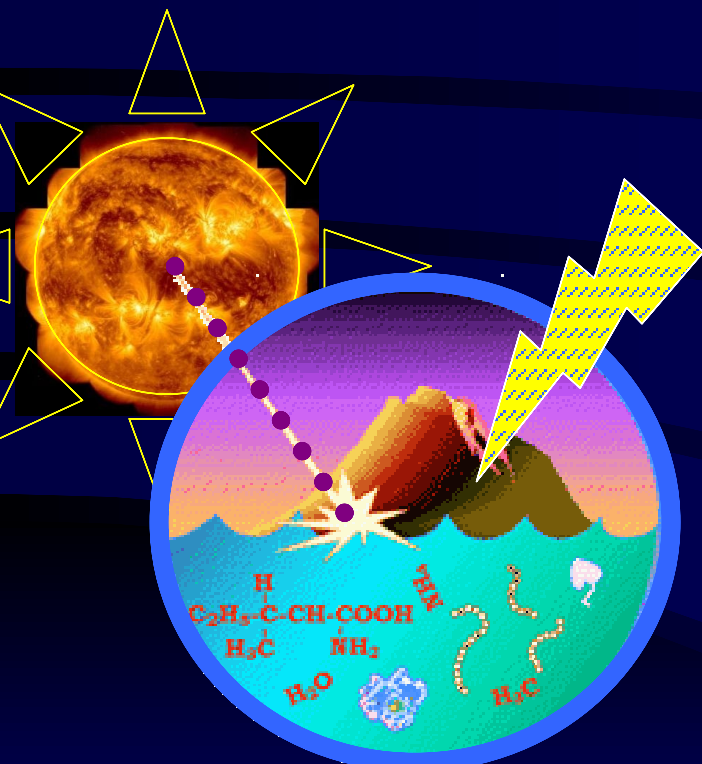
Earth, life, and solar activity

- Enable star/planetary-disk formation
  - magnetic field of proto-stellar cloud helps shed angular momentum to form star and dusty pre-planetary disk
- Star-disk coupling in the next 10 million years
  - stellar magnetic field couples to the pre-planetary disk, and transports angular momentum into the cloud
  - features: inner-cloud gap, polar jets, star-disk coupling
- Strong, energetic variability up to 1 billion years
  - activity-driven luminosity changes of up to 3-5%, (***darker*** with more starspots); irregular activity patterns
  - strong, highly energetic radiation
  - "ablation" of planet atmosphere by ionizing radiation (molecular destruction $\Rightarrow$ escape), and stellar wind or magnetic-field pickup (depending on planetary field)
- Declining activity at present for the aging Sun
  - Luminosity changes (***brighter*** **with more sunspots)** limited to 0.2-0.4%
  - Cycle modulations, including Maunder minima





Astrobiology:
Stellar activity and early life



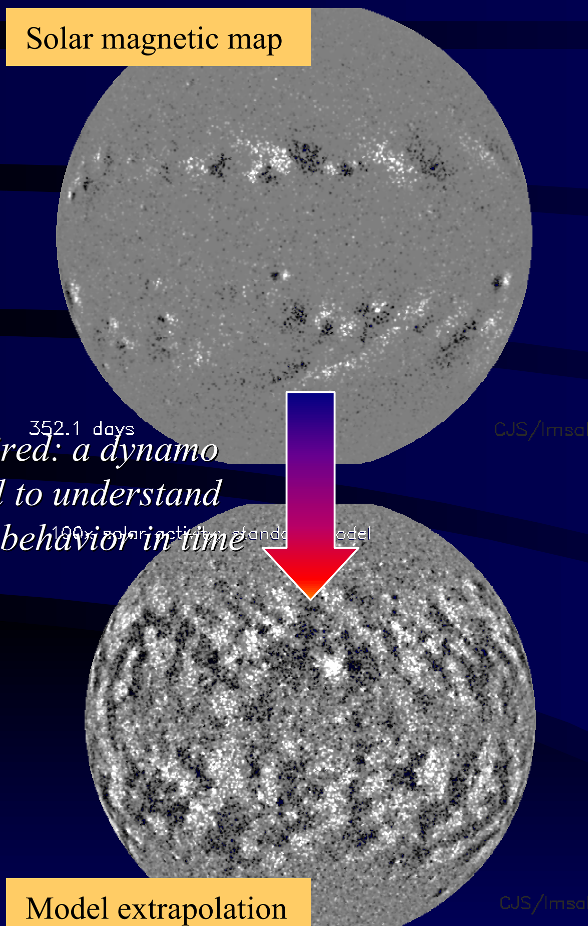
Goals:

- (5) "Establish limits for life in environments that provide analogues for conditions on other worlds"
  - Formation of terrestrial planets out of pre-planetary disk
- (6) "Determine what makes a planet habitable and how common these worlds are in the Universe"
  - Luminosity variations, stellar-wind effect on planetary atmosphere
- (10) "Understand the response of terrestrial life to conditions in space …"
  - Energetic radiation from stellar outer atmosphere (in quiescent phases and during flares) possibly more important than, e.g., lightning in formation of amino acids (Gaustad-Vogel study; Miller-Urey experiment)

Stellar activity is key to understanding life in the Universe and Earth's habitability

But there is no comprehensive model of solar and stellar magnetic activity

Forecasting Solar Activity



To forecast solar and heliospheric activity days to decades in advance, and to understand solar activity in the past, we need to develop and validate a dynamo model

- Testing grounds:
  - The Sun in detail
  - Population studies:
    - Stars like the Sun
    - Other ``cool'' dwarf & giant stars
    - Very young stars
    - Magnetically interacting binary stars

The Need for Observations of Other Stars

- To understand the dynamo, we need to know:
  - how magnetic fields are generated
  - how they behave in different circumstances: bifurcation patterns and domains for a complex, coupled, nonlinear system
- The sun is only one example
  - insufficient constraints on theories of dynamos, turbulence, structure, and internal mixing
- Observe other stars to ***establish how mass, rotation, brightness and age affect the patterns of activity***

Patterns in Stellar Activity

- What are the possible activity patterns?
  - How common is solar-like activity?
  - Can multiple cycles exist at the surface?
  - What are Maunder-minimum states like?
  - How do polar spots form?
  - What are extremely (in)active stars like?
  - What determines cycle strength and duration?

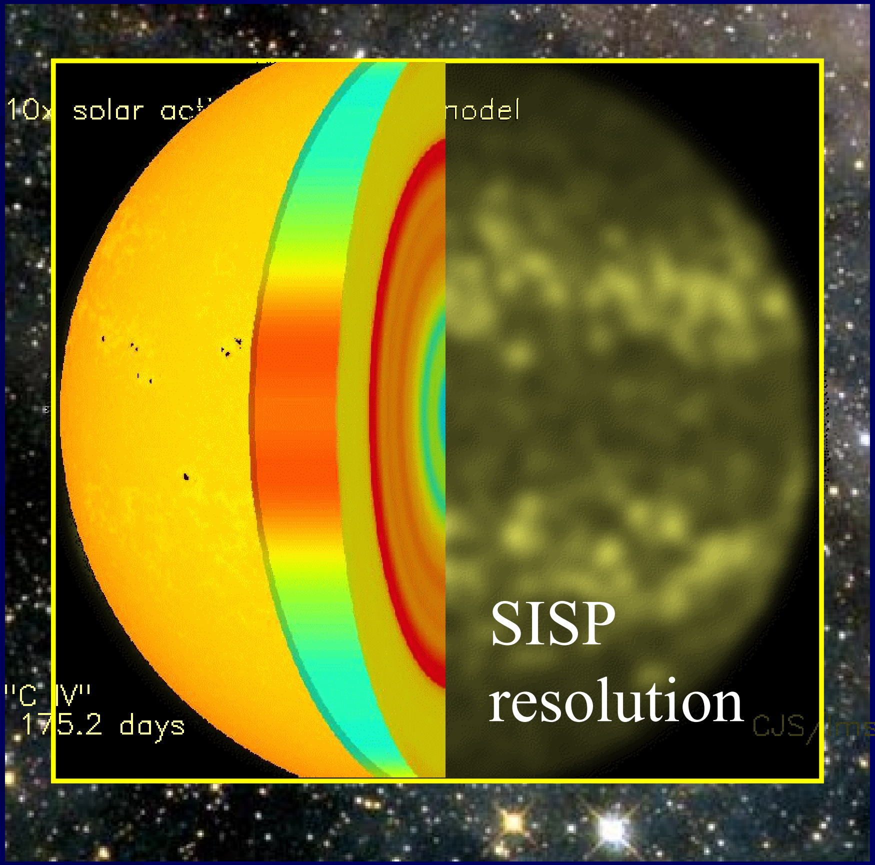
- These details cannot be provided by any single telescope in space or on the ground

Activity and Stellar Interiors

- Do we understand stellar interiors adequately?
- 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?

Imagine Seeing a Star Close Up!

- Activity modelers need:
  - Comparison stars
    - Atmospheric imaging
      - Field evolution
      - Differential rotation
      - Source properties of the magnetic field
    - Internal structure and rotation
  - Long solar and stellar records



Imagine Seeing a Star Close Up!

- Stellar structure studies will benefit from
  - acoustic imaging of the interior: asteroseismology
    - internal structure and basic physics
    - circulation and convection
  - direct surface imaging of convection on giant stars

Introducing the Stellar Imager and Seismic Probe

- SISP is a large space-based interferometer designed for high spatial 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

SISP Science Goals for SEC Living with a Star

- Perform comparative studies of the sun and stars
  - determine the temporal and spatial patterns of atmospheric activity and patterns in the sources of that activity and their dependence on stellar properties in order to understand the dynamo
- Understand magnetic activity cycles
- Ultimate Goal: achieve best-possible forecasting of solar activity on time scale of days to centuries

including Maunder-like minima and grand maxima that significantly affect geospace and the weather on earth

SISP Primary Science Goals: Origins & SEU

- 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, the formation of complex organic molecules, and the erosion of planetary atmospheres
    - 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

SISP Primary Performance Goals

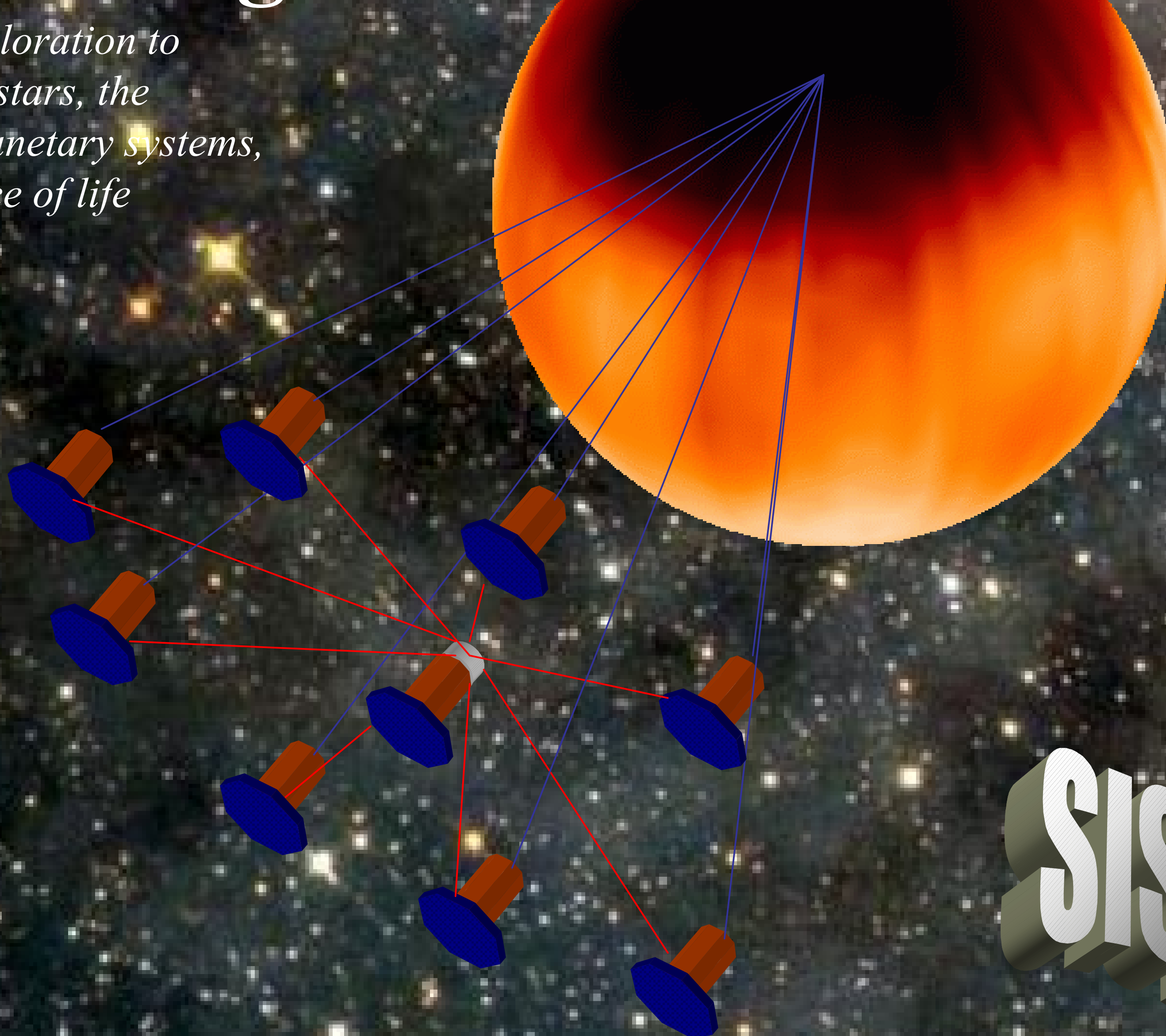
- Image different stars of different activity
  - for a substantial sample of nearby dwarf and giant stars, obtain a resolution of order 1000 pixels (~40,000 km on a Sun-like star)
  - study a sample in detail, revisiting over many years
  - measure:
    - sizes, lifetimes, and emergence patterns of 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 and rotation.

SISP Design Requirements

- Image stellar activity
  - High contrast at UV wavelengths
  - Obtain a stellar image as fast as possible to avoid rotational smearing and activity evolution
- Image stellar interiors
  - Short integration times for seismology (minutes for dwarf stars to hours for giant stars)
  - Low-resolution imaging to measure non-radial resonant waves (30-100 resolution elements)
  - Flexible interferometer configuration

Stellar Imager and Seismic Probe

A voyage of exploration to understand the stars, the formation of planetary systems, and the existence of life



SISP

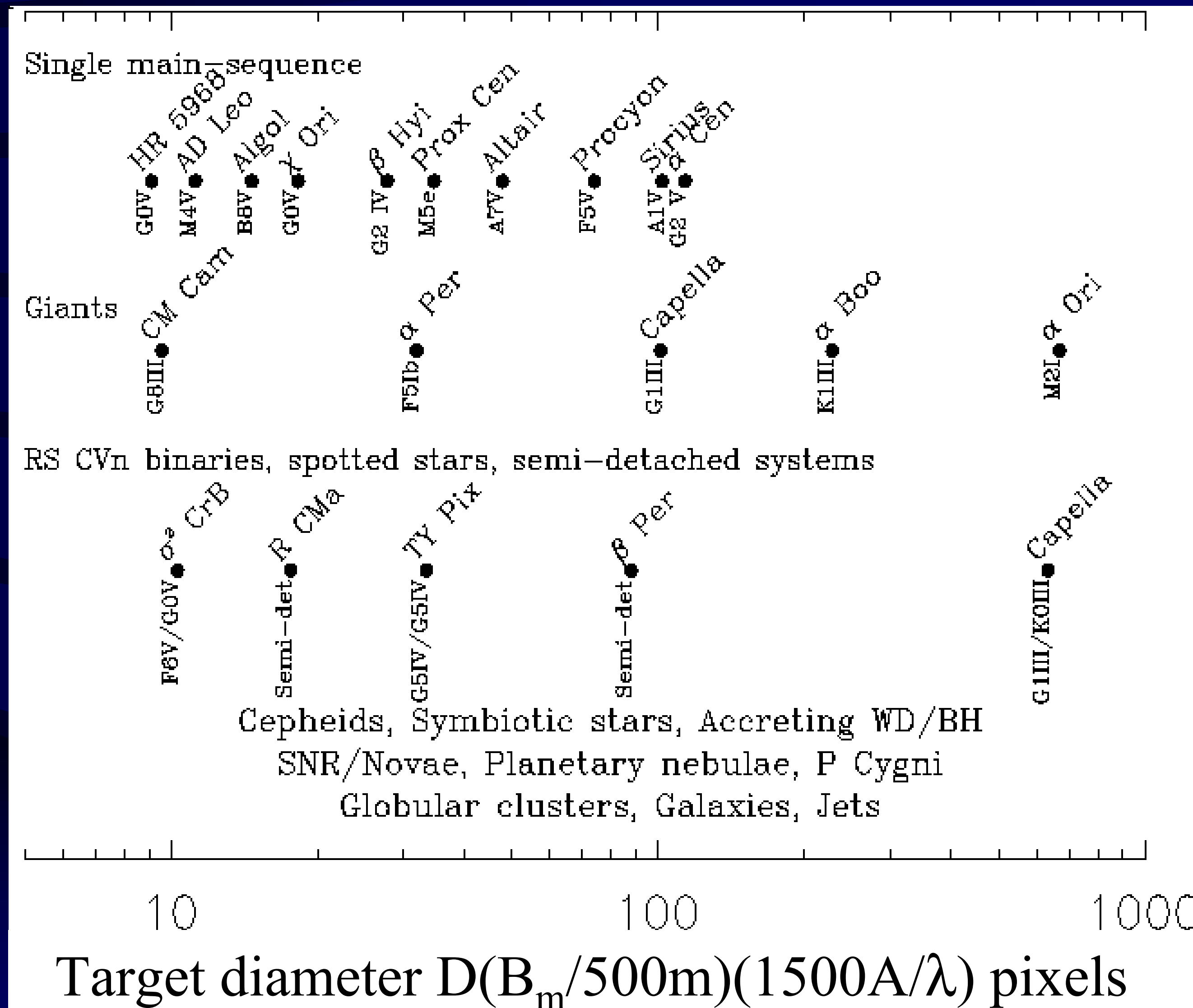
SISP Strawman Design

- 9 or more 1-meter class telescopes, plus central “hub”
  - » free-flying (micro-thrusters or sails) or single structure (boom network)?
- largest telescope-pair baseline at least 500 meters
  - » resolution: 60 micro-arcsec at 1500 Å and 120 micro-arcsec at 2800 Å
- observe in ~10-Ångstrom ultraviolet pass bands
  - » C^{3+} (100,000 K), Mg^{+} h&k (10,000 K)
- observe in broadband, near-UV or optical continuum
  - » image surface (3,000-10,000 K)
- reconfigure telescope formation for synthesis imaging
  - » expand/contract with limited rotation around central telescope?
- 5-10 year mission to study magnetic cycles
  - » individual telescopes can be refurbished or replaced as needed; the hub (“focal plane package”) can be replaced with upgraded component

SISP 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



More on SISP design

- Adequate time resolution for asteroseismology
  - obtain sufficient Fourier-component coverage fast enough to sample acoustic p-modes in dwarf stars?
    - a 9-telescope array provides 36 baseline pairs or 36 Fourier components (modes: $l < 10$-15 for Y-formation, or $m < 40$ for linear formation); operation in multiple pass bands can substantially increase this (by at least a factor 2-3).

- Orbit & S/C requirements to be evaluated
  - likely distant from Earth to avoid gravitational perturbations and light contamination: Sun-Earth L2 point ? - see ESA study)
  - consumables limited to ~10 kg for telescope repointing (ESA study)

SISP: When?

- SISP fits on strategic path of Origins interferometry mission
  - stepping stone towards crucial technology, while addressing science goals of 3 NASA/OSS research Themes
    - SISP is comparable in complexity to the ***Terrestrial Planet Finder***, and it may serve as a useful technological and operational pathfinder for the ***Planet Imager***: SISP resolution is ~40x less demanding than ultimate NASA goal
  - complementary to the planetary imaging interferometers
    - ***Terrestrial Planet Finder*** and ***Planet Imager*** null the stellar light to find and image planets
    - SISP images the central star to study the effects of that star on the habitability of planets and the formation of life on them.
    - TPF, SISP, and PI together provide complete views of other solar systems.

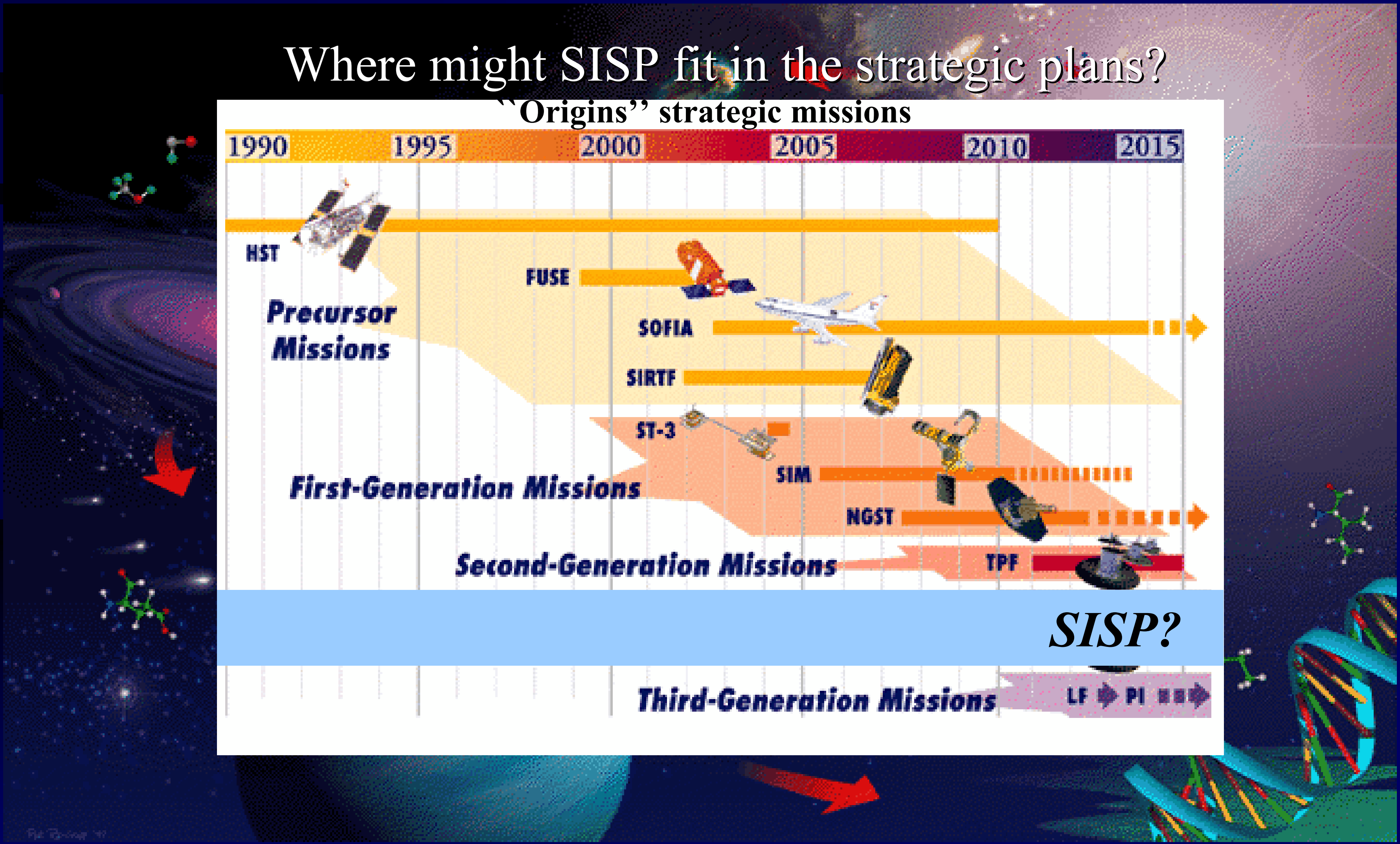
Synergies with other NASA Projects in Technology Development

- with Space Interferometry Mission, Terrestrial Planet Finder, and Planetary Imager projects
  - formation flying, pointing/stabilization/vibration control
  - determination of optimal array configuration
  - beam combining systems
  - optical path-length stabilization
  - metrology technology

Synergies with GSFC Projects in Technology Development

- with Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) development group
  - formation flying, (spinning) tethered systems
  - possibility of using fewer, but larger mirrors to get same Fourier uv-plane coverage
  - shared ground-based testbed
- with lightweight mirror technology development groups (NGST, others);may enable larger telescopes
- with developers of energy-resolving detectors
  - could enable broad-band and multiple narrow-band observations & multiple simultaneous baselines

SISP: a ``2-nd generation'' mission



SISP and TPF

Free-flying, multi-telescope, spectroscopic interferometers.

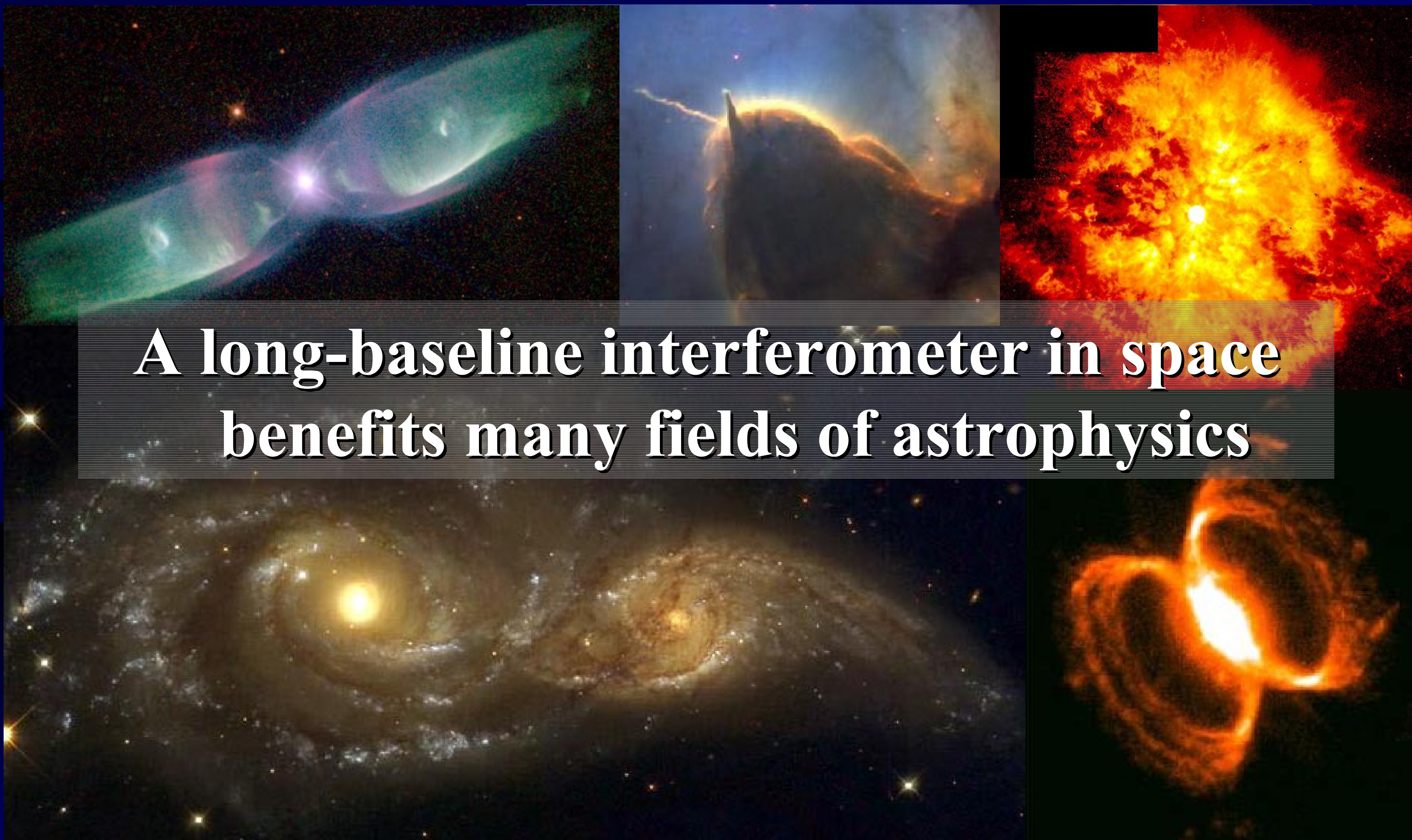
SISP:	*TPF:*
• Science focus on central star	• Science focus on planet atmospheres
• 1-meter class UV/optical	• 3.5-meter class near-IR, cryogenically cooled
• λ/50 baseline for 1% light loss: 3 nm precision	• nulling requires phase stability with 0.5 nm precision at 7-micron
• 8-10 telescopes	• 4-6 telescopes

Together they provide a complete view of other solar systems.

SISP Primary Science Impact

- Understanding of the solar dynamo in the past, present, and future, and an optimized ability to forecast solar activity
- High-resolution studies of stellar interiors
  - matter in extreme environments, and in stars different from the Sun: nuclear reactions, opacities, turbulence, convection & overshoot, transport processes of fields, particles, angular momentum, ...
  - initial abundances of He and Li, important for nucleosynthesis studies in the Big Bang
  - lepton physics and the weak interaction
    - neutrino physics (mass, oscillations) from Sun-like stars and cooling cores of giants through more accurate understanding of solar core

SISP and General Astrophysics



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

Other Science Goals: Origins & SEU (I)

- Active Galactic Nuclei
  - transition zone between broad and narrow-line region
  - origin and orientation of jets
- Quasi-stellar Objects & Black Holes
  - resolve close-in structure, especially radiation from accretion processes
- Supernovae
  - direct information on close-in spatial structure
  - role in galaxy evolution: injection of kinetic energy and metal-enriched material into interstellar medium (important for evolution of life and presence of terrestrial-type planets)

Other Science Goals: Origins & SEU (II)

- Stellar interiors
  - internal structure, including, e.g., opacities, in stars outside solar parameters or of very different composition
    - need for element-specific opacity tables?
    - can abundances in the solar core be off by up to 15%?
- Hot Stars
  - hot polar winds, non-radial photospheric pulsations
  - luminous blue variables, like η Car (possible progenitors to γ-ray bursters)
  - envelopes and shells of Be-stars
- Spectroscopic binary stars / apparently single stars
  - observe companions, measure orbits, and determine stellar properties for key tests of stellar evolution

Other Science Goals: Origins & SEU (III)

- More on Cool, Evolved Giant & Supergiant Stars
  - spatio-temporal structure of extended atmospheres/winds
  - long-period variable stars and semi-regular variable stars
    - see changes in diameters with wavelength
    - image shock fronts passing through extended atmospheres
- Interacting Binary Stars
  - resolve mass-exchange
  - see dynamical evolution and accretion
  - understand why their dynamos are more efficient

Science and Technical Questions yet to be addressed

- What time and spatial resolution really needed?
- Is Fizeau or Michelson design best?
- Can energy-resolving detectors be used to greatly enhance science productivity?
- Should the array be tethered and/or spinning?
- How many elements of what size are optimal for sampling the uv-plane efficiently?
- What photometric accuracy can be achieved?
- What is the impact of side-lobes?

Design/Requirements Study

- fully define concept
- define/refine science requirements & goals based on community input
- identify technical challenges and needs
- followed by more detailed proposals to NASA/HQ

SISP in the Near Future (I)

- Presentations at NASA/HQ&GSFC
- Development of a web site: http://www.lmsal.com/SISP
- An informal Concept Development Group is being assembled to further develop the concept
  - encourage involvement from other interested parties (presentations at meetings such as AAS/SPD/AGU ?)
  - preparation of a ``white paper'' to describe science goals and technology requirements.
- Identify possible collaborations with other study groups (e.g., TPF; SPECS, light-weight mirrors, energy-resolving detectors at GSFC; ...)

SISP in the Near Future (II)

- Currently on the Concept Development Group:
  - LMMS/ATC: Karel Schrijver (LMMS science lead), ...
  - NASA-GSFC: Ken Carpenter (GSFC science lead), Lee Feinberg (GSFC engineering lead), Dick Fisher (LASP director), Joe Davila
  - Catholic Univ.: Rich Robinson, Fred Bruhweiler
  - U. Colorado: Alex Brown, Jeff Linsky, Jon Morse
  - STScI: Steffi Baum
  - CFA: Andrea Dupree, Lee Hartmann
  - Mt.Wilson Obs.: Sallie Baliunas
  - U. Vienna/Potsdam: Klaus Strassmeier
  - U. Aarhus: Jörgen Christensen-Dalsgaard
  - Kiepenheuer Inst.: Oscar Van der Lühe (director)
  - SUNY: Fred Walter
  - Yale: Pierre Demarque

The impact of the Stellar Imager and Seismic Probe

Imaging stars and their environments and measuring their internal structure and dynamics constitute a voyage of discovery and exploration that will

- outdate theories that take stars to be static, layered spheres
- deepen our understanding of a broad range of physical processes
- strengthen the foundation of our view of the universe
- help forecast the activity of the Sun for our society that is living with a star

Background Information

- SEU Theme Quests
- Origins Theme Goals
- SEC Quests
- Useful References

SEU Quests

- Quest 1: Beyond the Big Bang
  - Seeds of Galaxies, Universal Expansion, Dark Matter
- Quest 2: Black Holes
- Quest 3: Extremes of Energy and Matter
  - Quasi-Stellar Objects, GRB’s, Grav. Radiation/Waves, Cosmic Rays
- Quest 4: Lives of Stars
  - Star birth, Fusion -> starlight and elements for life, explosions

Origins Goals

- Goal 1
  - understand how galaxies formed in the early universe and understand the role of galaxies in appearance of planetary systems and life
- Goal 2
  - understand how stars and planetary systems form and to determine whether life-sustaining planets exist around other stars in the solar neighborhood
- Goal 3
  - understand how life originated on earth and determine whether it began and may still exist elsewhere as well

SEC Quests

- Quest 1: Why does the Sun vary?
- Quest 2: How do the planets respond to solar variations?
- Quest 3: How do the Sun and the galaxy interact?
- Quest 4: How does solar variability affect life and society?

Useful References

- Books/studies on interferometry
  - "Kilometric Baseline Space Interferometry", ESA SCI(96)7, June 1996, Bely et al.
  - "Synthesis Imaging in Radio Astronomy", ASP Conf. Ser., vol. 6, 1994, eds. Perley, Schwab, Bridle
- Web sites on interferometers
  - SIM: sim.jpl.nasa.gov
  - TPF: tpf.jpl.nasa.gov
  - SPECS: space.gsfc.nasa.gov/astro/specs

Useful References

- Books
  - Stellar activity (conference proceedings):
    - "Stellar Surface Structure," IAU Symp. 176, Strassmeier & Linsky, Kluwer (1996)
  - Stellar activity, climate, and life
    - "The Sun in time," Sonett, Giampapa, & Shapley, University of Arizona Press (1991)
- Other web sites:
  - Astrobiology: astrobiology.arc.nasa.gov/