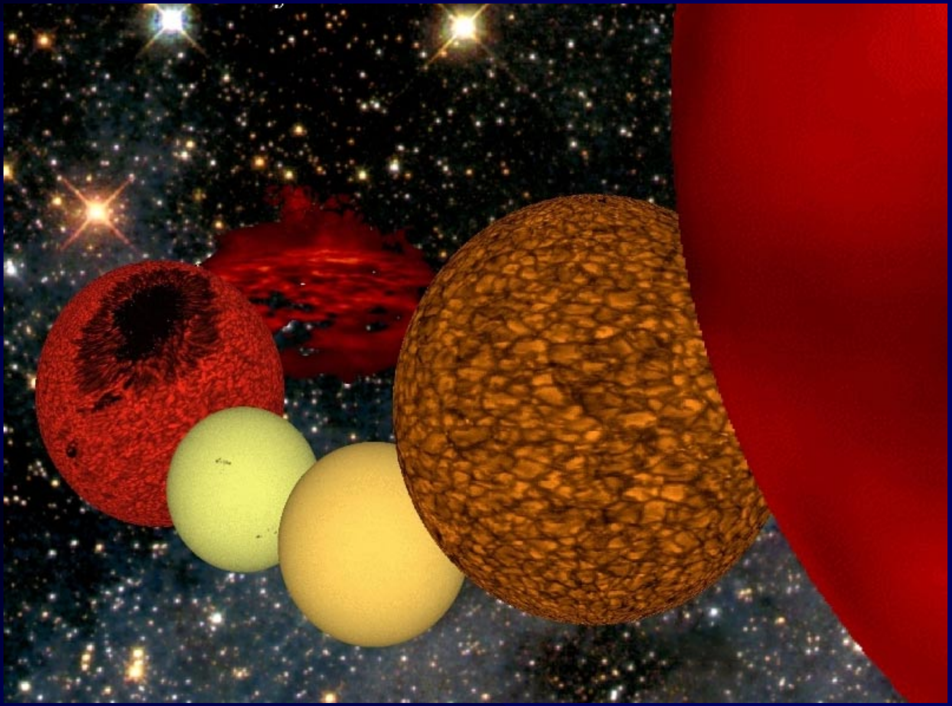
Understanding the Stellar Dynamo, Solar/Stellar Variations, and Their Impact on Life and the Habitability of Planets:

The Science of the *Stellar Imager*



K. G. Carpenter (NASA/GSFC) and C. J. Schrijver (LMMS)

NASA HQ Lunch Seminar: 10/18/00

The Importance of Understanding Stars

- The Sun is only one of many classes of stars
- Our close-up view of the Sun has enabled discoveries that have 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)
- Understanding stars in general is the foundation for understanding the Universe

The Importance of Stellar Dynamos

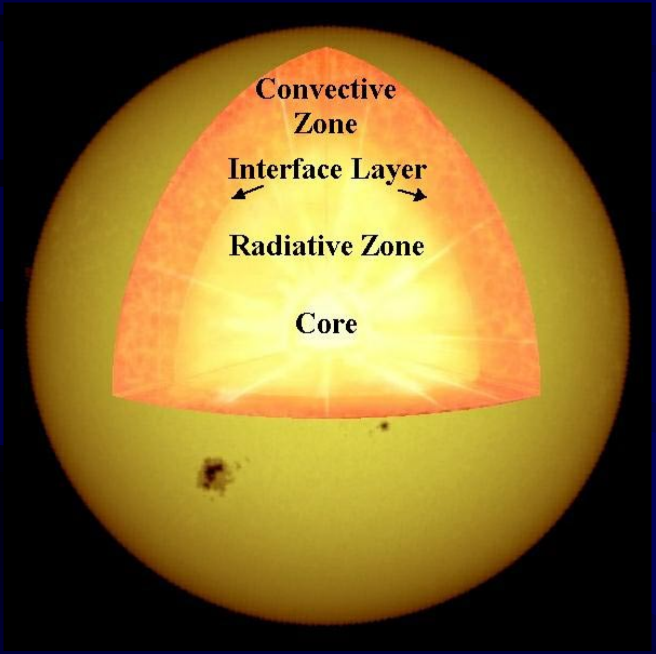
The Dynamo is an ensemble of electric currents flowing in the subsurface layers of a star. It produces a complex magnetic field topology and induces associated activity which makes stars (including the sun) ever-changing and "dynamic"

The stellar magnetic field

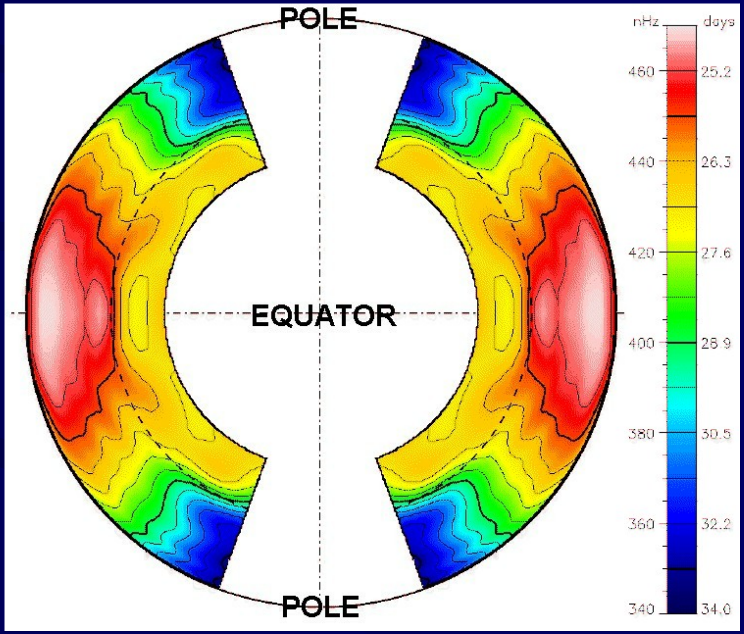
- slows the rotation of the collapsing cloud, enabling star formation
- couples evolution of star and pre-planetary disk
- results in energetic radiation conducive to the formation (& destruction) of complex molecules
- governs the habitability of the biosphere through space weather and planetary climate through luminosity, wind, magnetic fields, and radiation

The Convection Zone

The Dynamo is likely concentrated at the Interface Layer: the depth of the convective zone is an important parameter to know

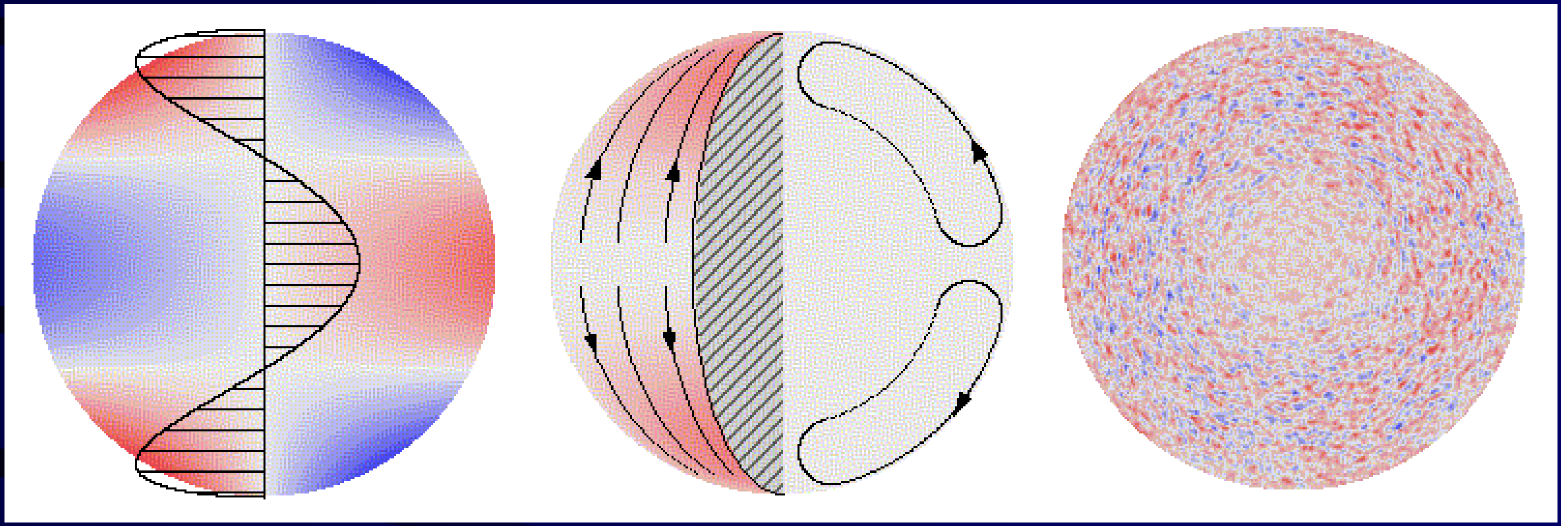


Radial Structure of Sun



Internal rotation rate of sun

Flows on the Sun

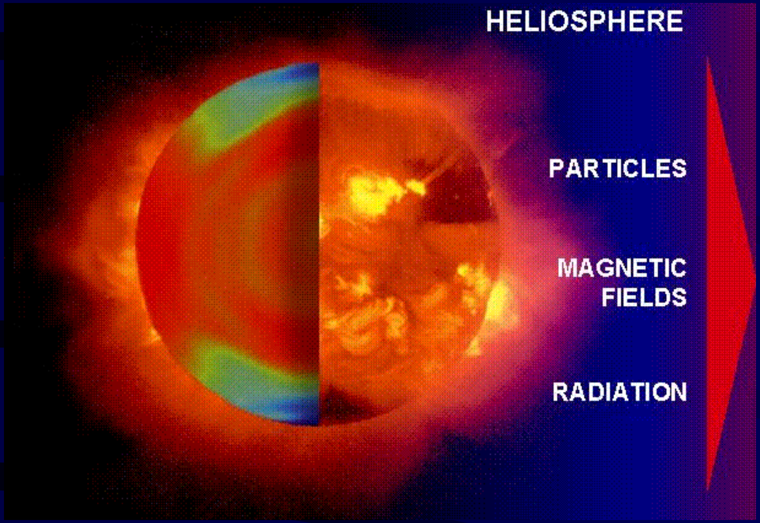


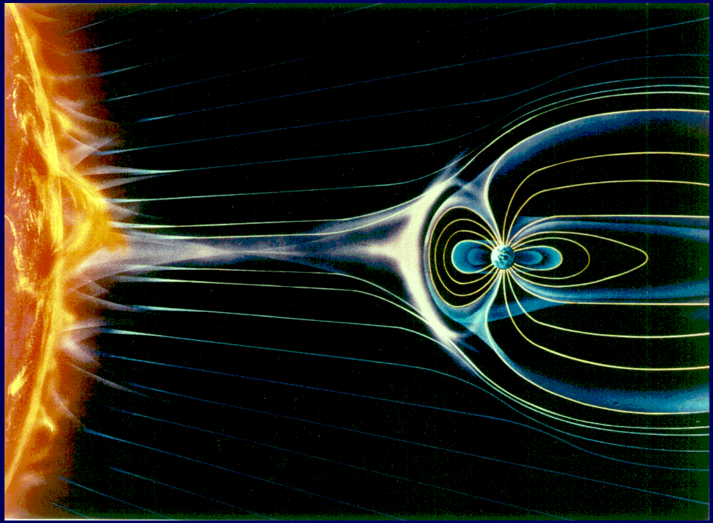
Differential Rotation

Meridional Flow

Convective Supergranulation

Manifestations and Effects of Stellar Magnetic Activity

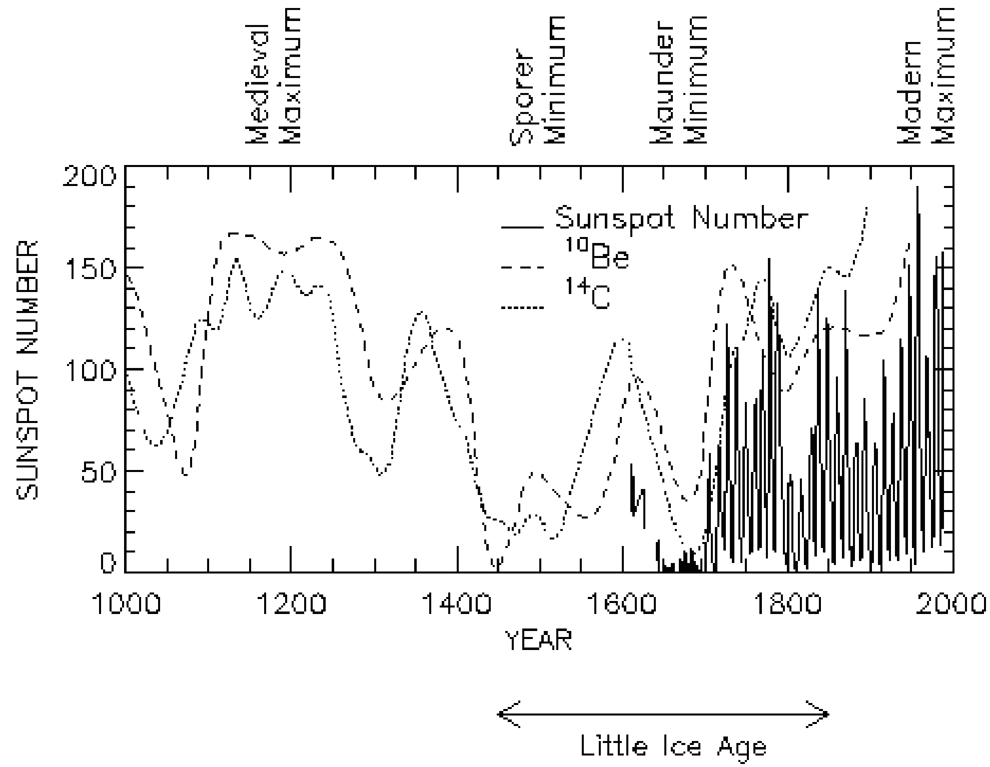




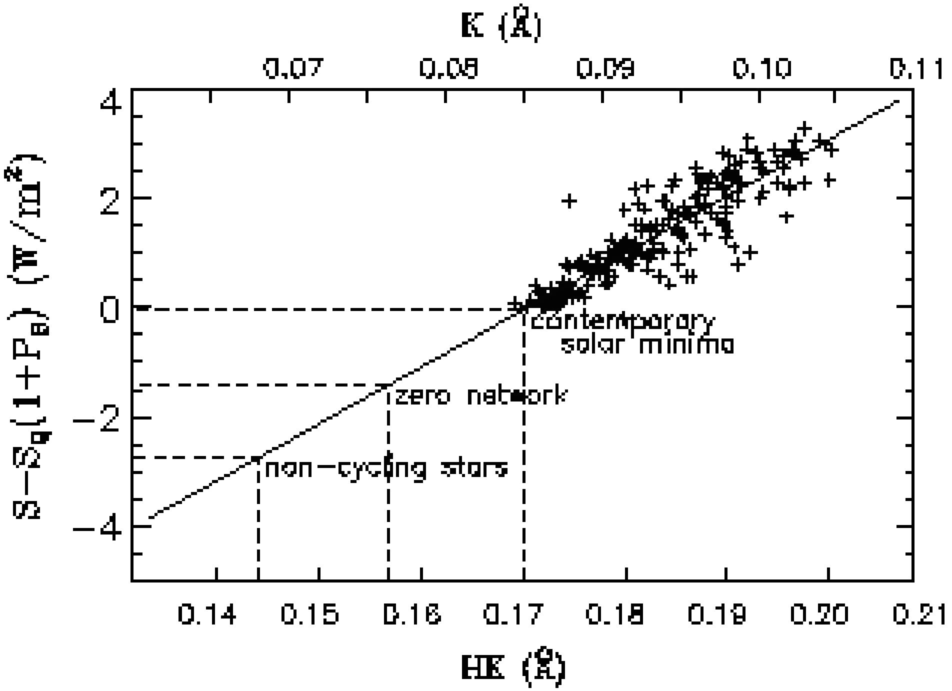
- Solar luminosity shows cyclic changes
  - induced climate changes on Earth, such as the 17th-Century Little Ice Age during the solar Maunder minimum

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

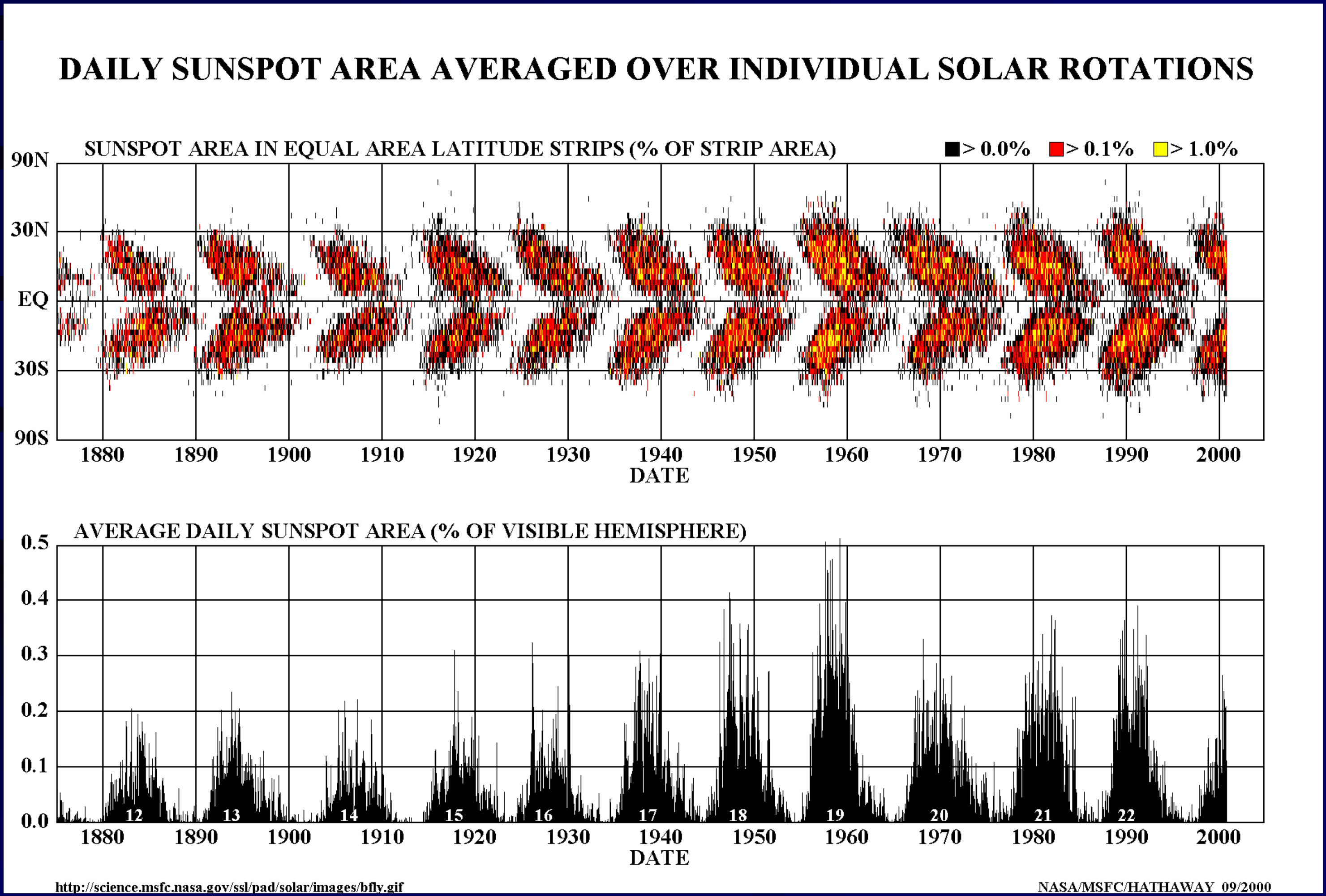
Solar Variations Since AD 1000



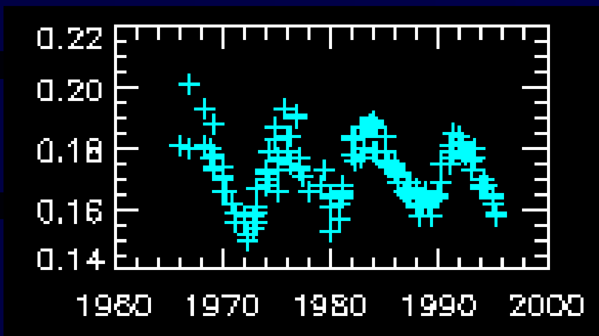
Solar Activity Measured by Ca II and Total Irradiance



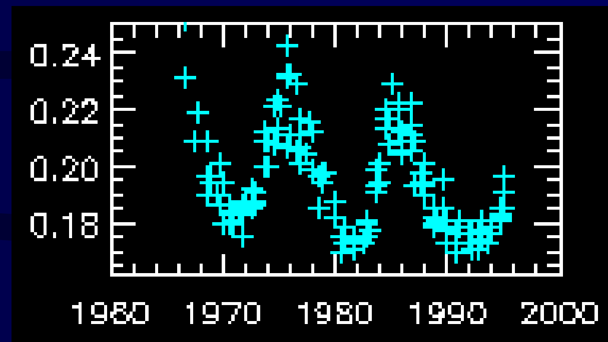
Spatial/Temporal Patterns of Solar Activity: The Butterfly Diagram & #spots vs. time



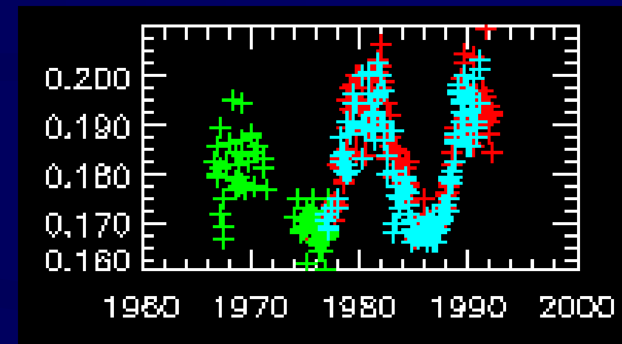
Temporal Patterns of Stellar Activity I.: Disk-Integrated Ca II Light (Mt. Wilson Program)



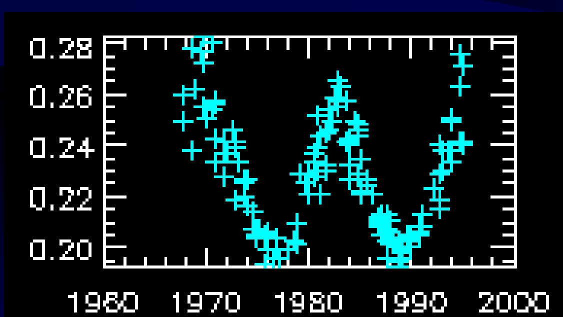
HD 81809: 8.2 yrs



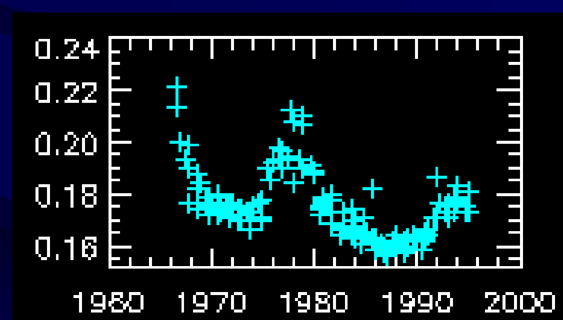
HD 10476: 9.6 yrs



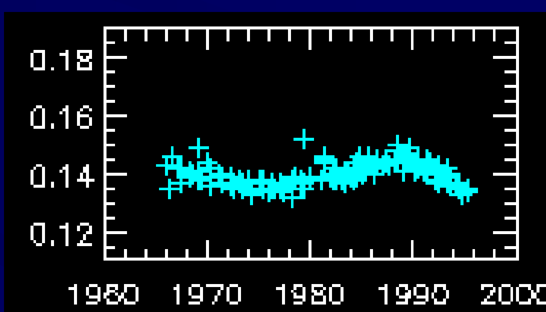
The Sun: 10 yrs



HD 16160: 13.2 yrs

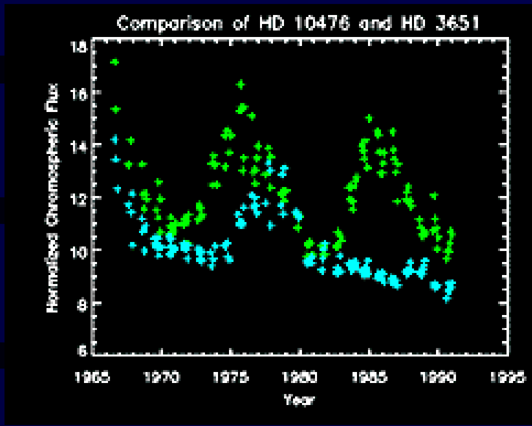


HD 3651: 13.8 yrs

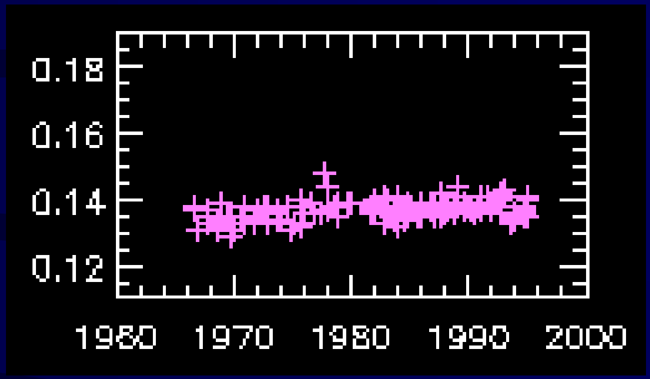


HD 136202: 23 yrs

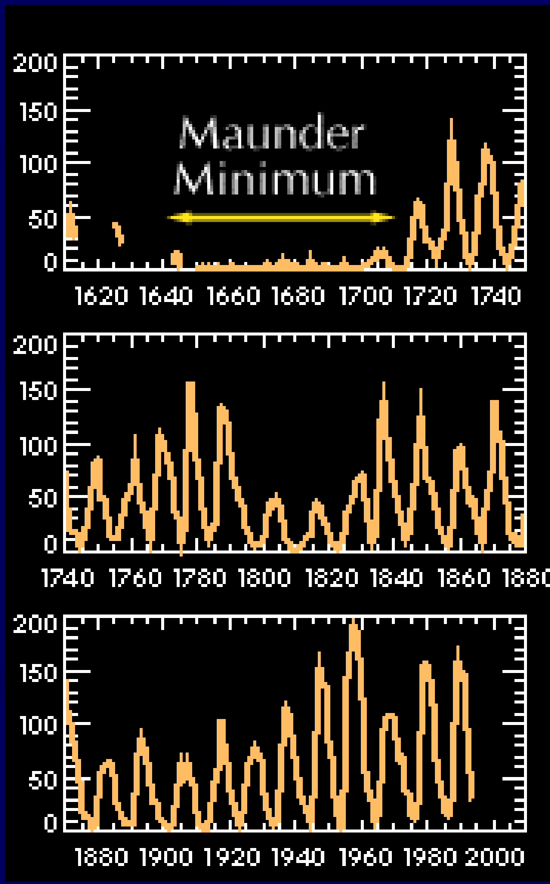
Temporal Patterns of Stellar Activity II: Ca II “Maunder-Minimum” Stars (Mt. Wilson Prog.)

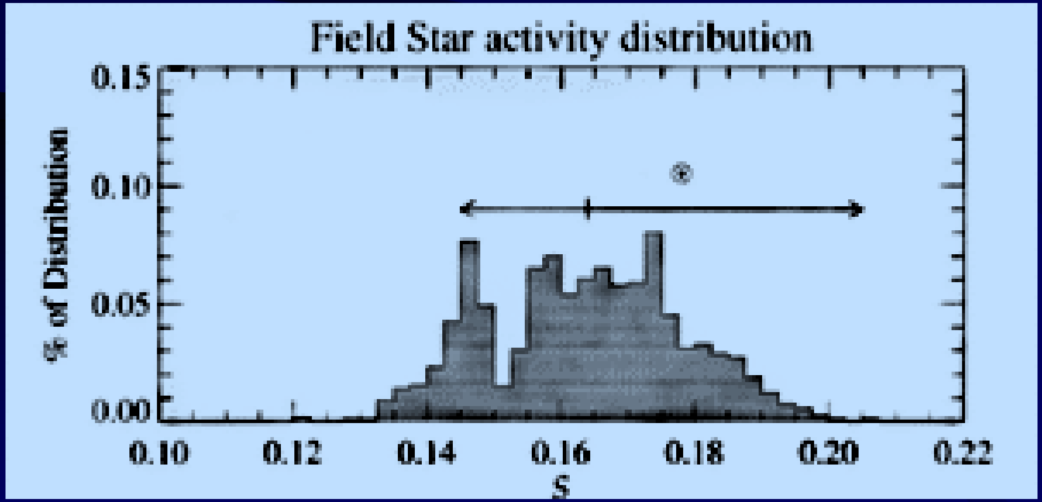


HD 10476 & 3651

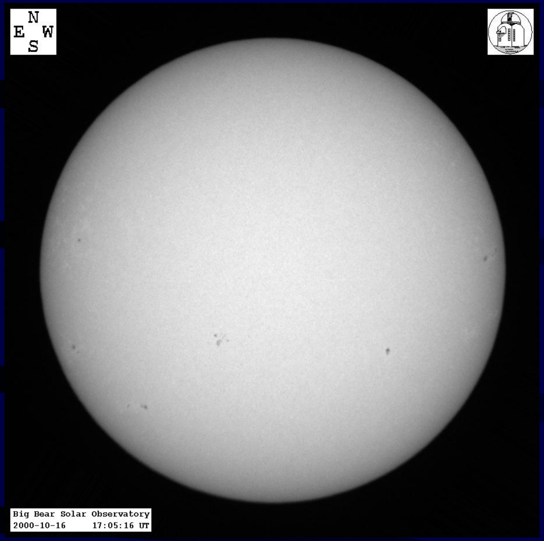


HD 9562: mmin

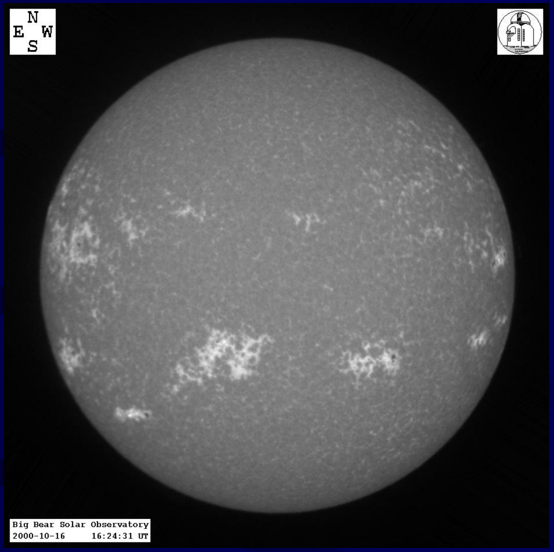




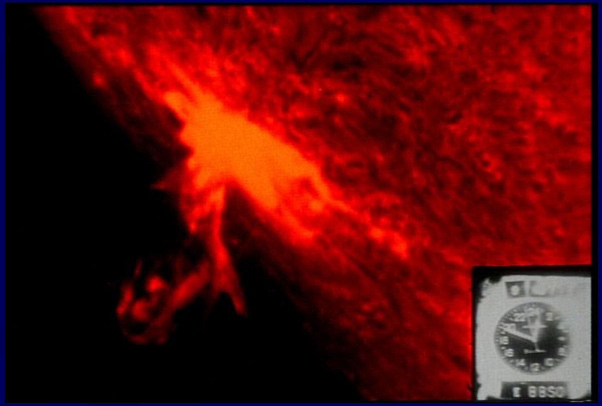
Solar Activity Diagnostics



Sunspots



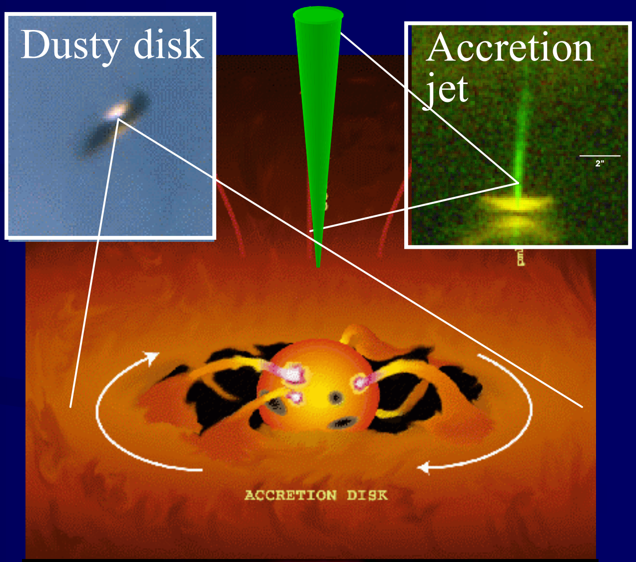
Plages

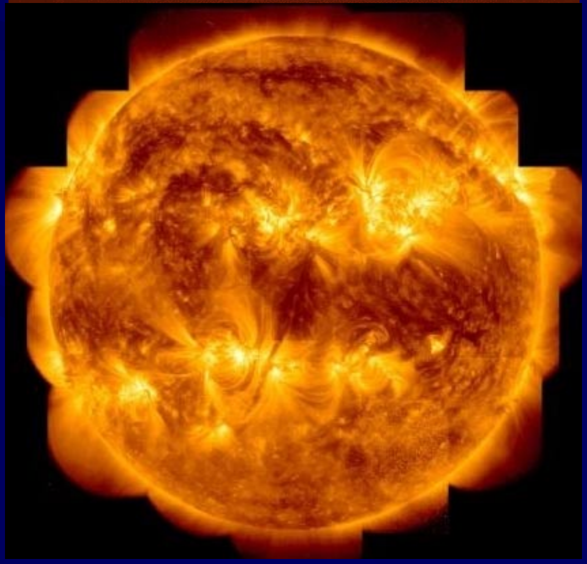


Flares

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





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

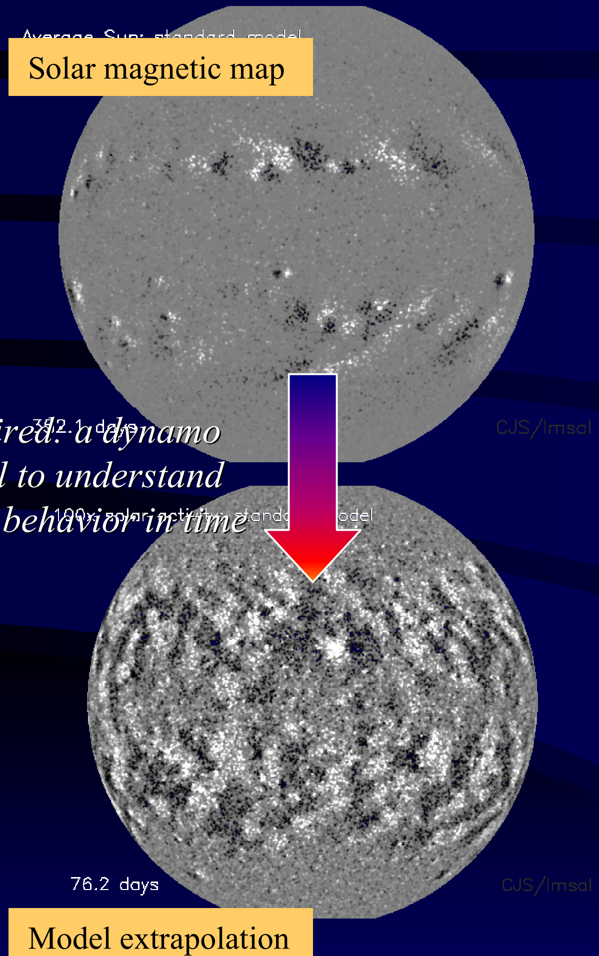
Current Impacts of Solar Activity on Earth (II)

- 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

Stellar activity produced by the dynamo is key to understanding life in the Universe and the habitability of earth and other planets

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

Space-Weather & Earth-Climate Forecasting (I)

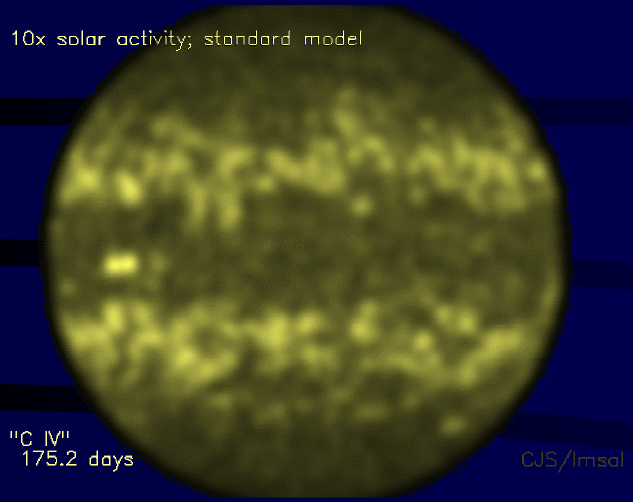


Required: a dynamo model to understand solar behavior in time

We must develop and 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

Space-Weather & Earth-Climate Forecasting (II)



Testing grounds for dynamo models:

- 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 a Population Study of Cool Stars

- To understand the dynamo, we need to know how magnetic fields are generated and how they behave in different circumstances
- The sun is only one example
  – provides insufficient constraints on theories of dynamos, turbulence, structure, and internal mixing
  – must observe other stars to *establish how mass, rotation, brightness and age affect the patterns of activity* & determine:
    - What determines cycle strength and duration?
    - 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?

Understanding the sub-surface layers of a star: Asteroseismology

- Although its clearest manifestations are visible on the stellar surface, a full understanding of the dynamo requires a knowledge of the subsurface layers of the star in which it resides
- Asteroseismology (acoustic imaging) of the star enables us to address questions related to the stellar interior
  - 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?

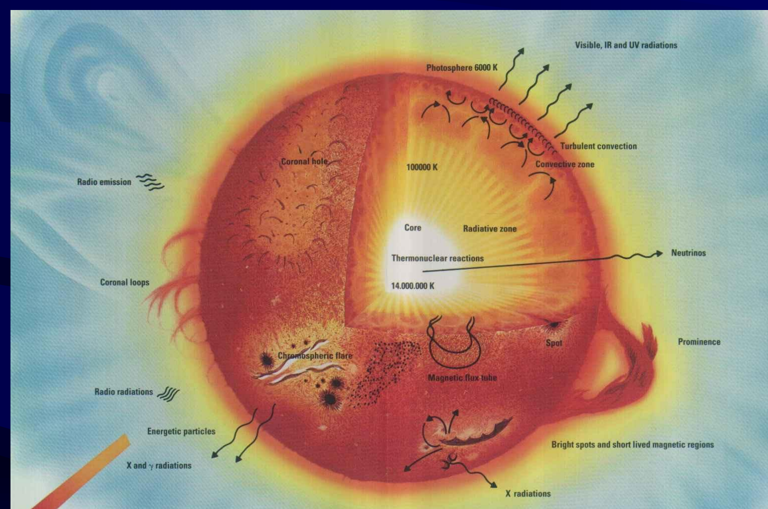
Furthering our Understanding of Solar/Stellar Magnetic Activity & its Effect on Life in the Universe: Introducing the *Stellar Imager (SI)*

- *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

Of all the stars in the Universe

only one has been seen as it truly is…

infinitely complex and ever-changing -



Just imagine seeing other stars close up …

Concept Development Group

- NASA-GSFC: Ken Carpenter, Lee Feinberg, Dick Fisher, Joe Davila
- LMMS/ATC: Carolus Schrijver, Domenick Tenerelli
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- Catholic Univ.: Fred Bruhweiler
- U. Colorado: Alex Brown, Jeff Linsky, Jon Morse
- Ball Aerospace: Steve Kilston
- STScI: Ron Allen
- CFA: Andrea Dupree, Lee Hartmann
- Mt.Wilson Obs.: Sallie Baliunas
- SUNY: Fred Walter
- Yale: Pierre Demarque

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 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 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

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

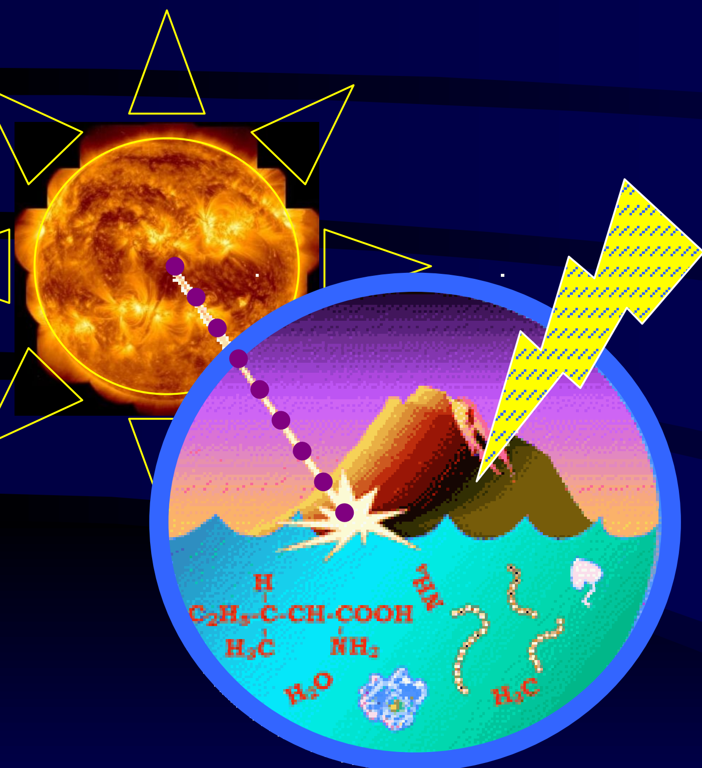
Goal 2: understand how stars and planetary systems form and determine whether life-sustaining planets exist around other stars in the solar neighborhood

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?

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)

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”

Living With a Star

Primary Performance Goals

- Image different stars of different activity
  - for a substantial sample of nearby dwarf and giant stars, obtain a resolution ~ 1000 pixels on disk (33x33) (~50,000 km^2/pixel 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.

Design Requirements (I)

- Imaging of stellar surface activity requires
  - UV images: for visibility of surface manifestations of dynamo
    - dark starspots in photosphere (seen in visible light) are small in most stars & surrounding bright stellar surface makes them difficult to detect without superb resolution and very low scattered light
    - bright chromospheric (10,000-20,000 K, e.g. Mg II h&k 2800 A lines) and transition-region (50,000-500,000 K, e.g. C IV 1550 A doublet) UV emission originates from plages above surface wherever it is penetrated by strong magnetic fields
    - plages are more extended than starspots and show much higher contrast against the weak UV photospheric thermal emission, 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

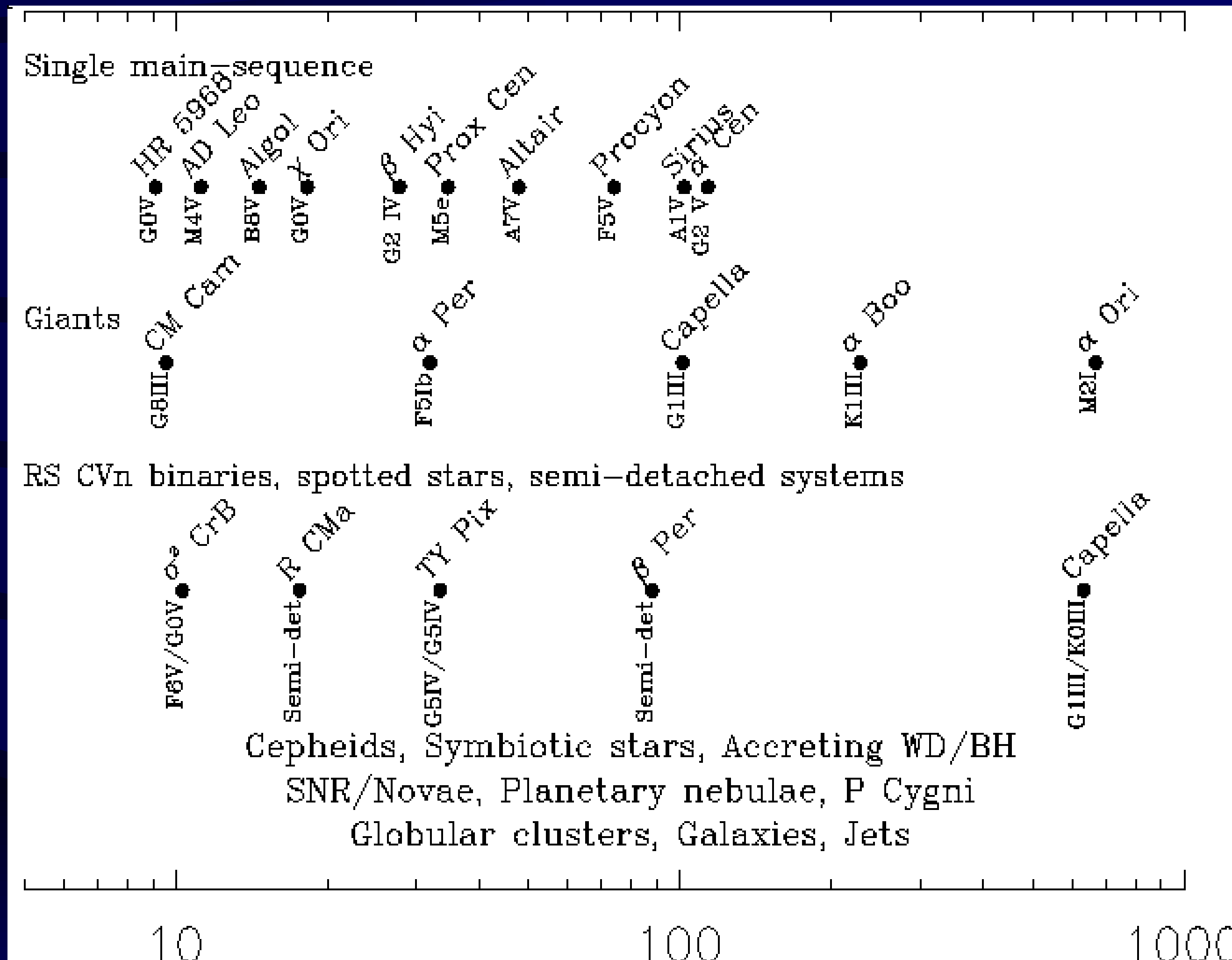
Design Requirements (II)

- Imaging of stellar interiors requires
  - Short integration times for seismology (minutes for dwarf stars to hours for giant stars)
    - broadband optical wavelengths desirable to get higher fluxes
  - Low-resolution imaging to measure non-radial resonant waves (30-100 total resolution elements)
    - along the equator to reconstruct internal structure
    - across the surface to measure differential rotation of deep convective envelope
- Flexible interferometer configuration required for both types of imaging

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



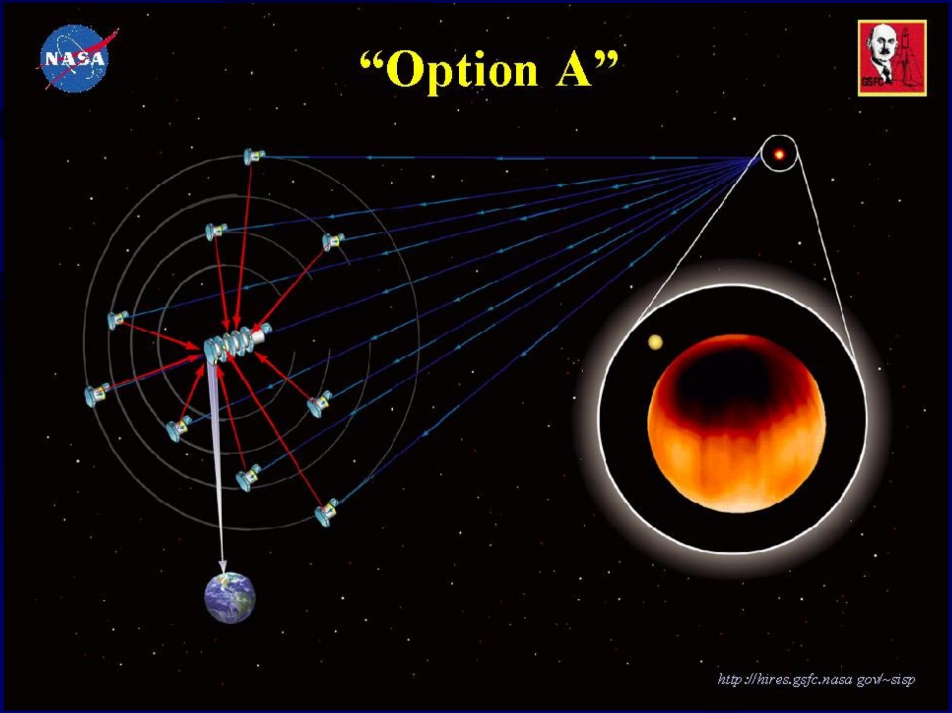
Target diameter $D(B_m/500m)(1500A/\lambda)$ pixels

Basic Strawman Design Elements

- The Stellar Imager is a large space-based UV-optical interferometer with
  - 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
  - largest telescope-pair baseline at least 500 meters
  - observes in
    - ~10-Ångstrom UV pass bands (C^{3+} (100,000 K), Mg^{+} h&k (10,000 K))
    - broadband, near-UV or optical continuum (3,000-10,000 K)
  - telescope formation reconfigurable for synthesis imaging
  - 5-10 year mission to study stellar activity/magnetic cycles:
    - individual telescopes/central hub can be refurbished or replaced as needed
  - Array Configuration and Element Size/Type
    - Option A: ~10 1-meter class telescopes, plus central hub
    - Option B: ~30 1-meter class flat mirrors, plus central hub

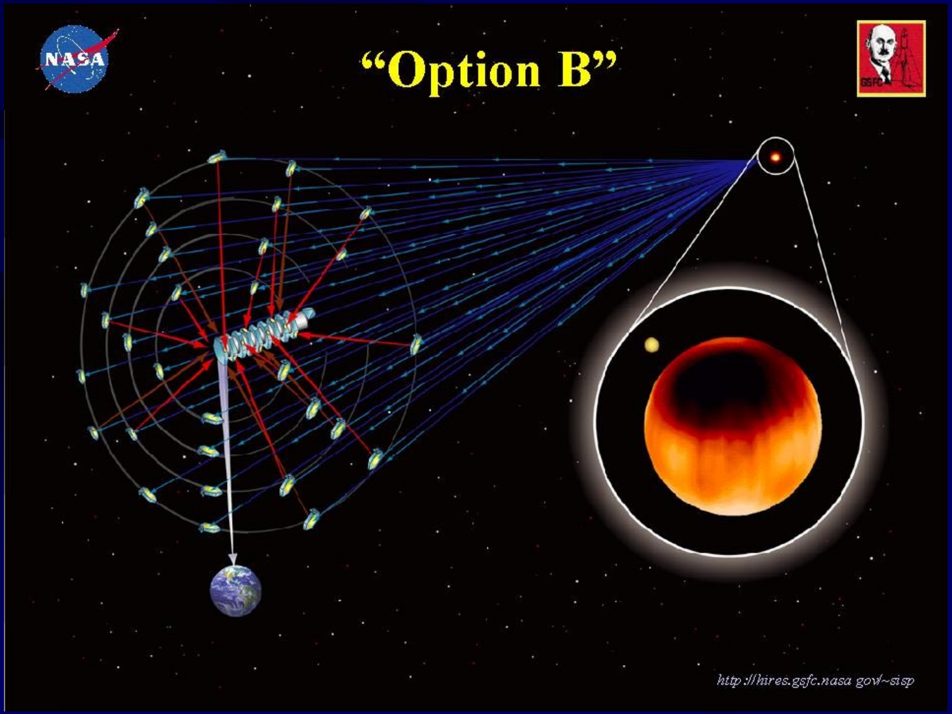
Mission Concept "A"

- 9 or more 1-meter class telescopes as array elements
- central hub
  - telescope to provide zero-phase information
  - optics to combine and interfere beams
- requires numerous reconfigurations of array to obtain synthesized image, but less complex hub than Option B



Mission Concept "B"

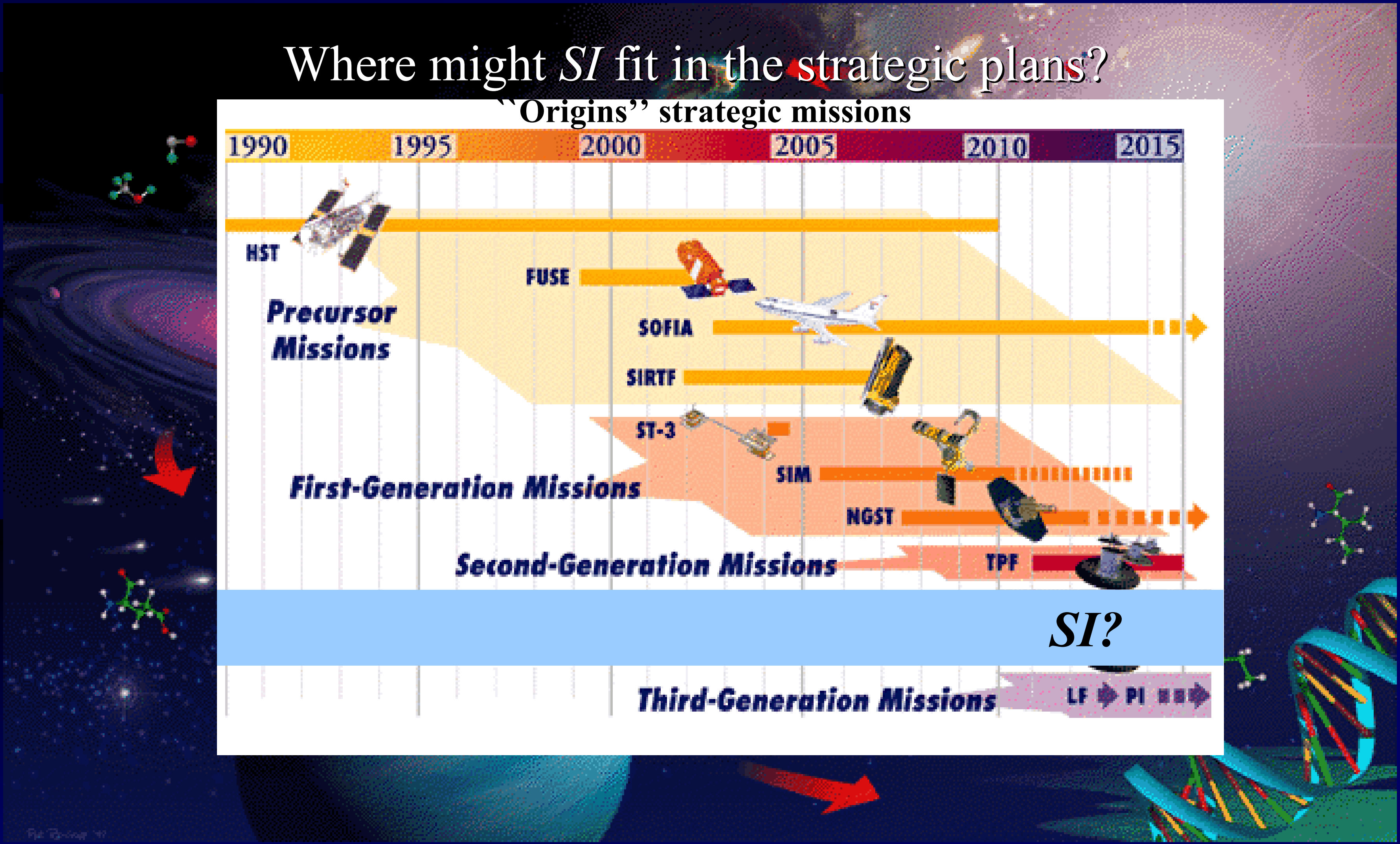
- ~30 one-meter class flat mirrors as array elements
- central hub
  - telescope to provide zero-phase information
  - optics to reduce, combine and interfere beams (likely Fizeau design)
- requires fewer reconfigurations of array to obtain synthesized image, but more complex hub than Option A



Place in NASA/ESA Strategic Roadmaps

- The Stellar Imager (SI) is on the strategic path of the 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 ESA & NASA planetary imaging interferometers
    - ***Terrestrial Planet Finder***, ***IRSI/Darwin***, and ***Planet Imager*** null the stellar light to find and image planets
    - ***SI*** 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, Darwin, & PI together provide complete views of other solar systems

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



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

SI and TPF

Both are free-flying, multi-telescope interferometers, with spectroscopic capabilities.

- SI:
- Science focus on central star
- 1-meter class UV/optical
- λ/50 baseline for 1% light loss: 3 nm precision
- 8-10 telescopes

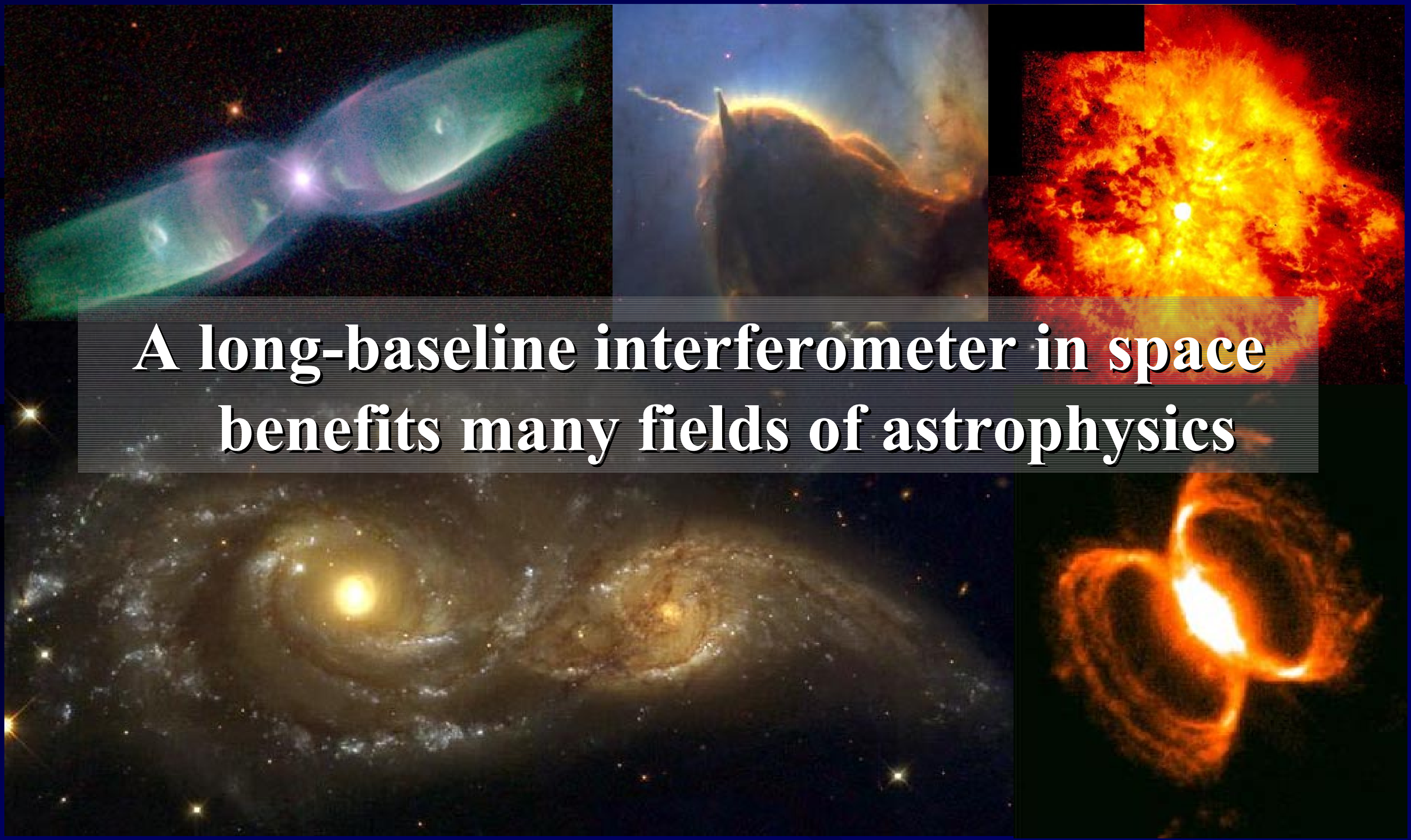
TPF

- Science focus on planet atmospheres
- 3.5-meter class near-IR, cryogenically cooled
- nulling requires phase stability with 0.5 nm precision at 7-micron
- 4-6 telescopes

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

SI and General Astrophysics



Other Science Topics: 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 & metal-enriched material into ISM (important for evolution of life/terrestrial-type planets)
- 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%?

Other Science Topics: Origins & SEU (II)

- Hot Stars
  - hot polar winds, non-radial photospheric pulsations
  - luminous blue variables, like η Car (possible progenitors to GRB’s)
  - 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
- Interacting Binary Stars
  - resolve mass-exchange; see dynamical evolution and accretion
  - understand what causes their dynamos to be more efficient
- More on Cool, Evolved Giant & Supergiant Stars
  - spatiotemporal structure of extended atmospheres/winds
  - long-period variable stars and semi-regular variable stars
    - see changes in diameters vs. wavelength
    - shock fronts passing through extended atmospheres

Current Status

- Included in far-horizon SEC Roadmap (summer 1999)
- Mission concept further developed by
  - C.J. Schrijver (Stanford-Lockheed Institute for Space Research)
  - K.G. Carpenter (LASP - NASA/GSFC)
  - in consultation with informal Concept Development Group
- Presentations of mission concept
  - October, 1999 Cool Stars, Stellar Systems, & the Sun Conference
  - NASA GSFC and HQ on March 6 and March 14, 2000
  - June, 2000 AAS and SPD meetings
- Web site created: **http://hires.gsfc.nasa.gov/~sisp**
- "white paper" written to describe science goals/technology req'ts
- Included in SEC "State of the Theme" report (May, 2000)
- next steps
  - Architecture/Feasibility Studies
  - ground-based Testbed Development Program

The Impact of the Stellar Imager

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

Living With a Star