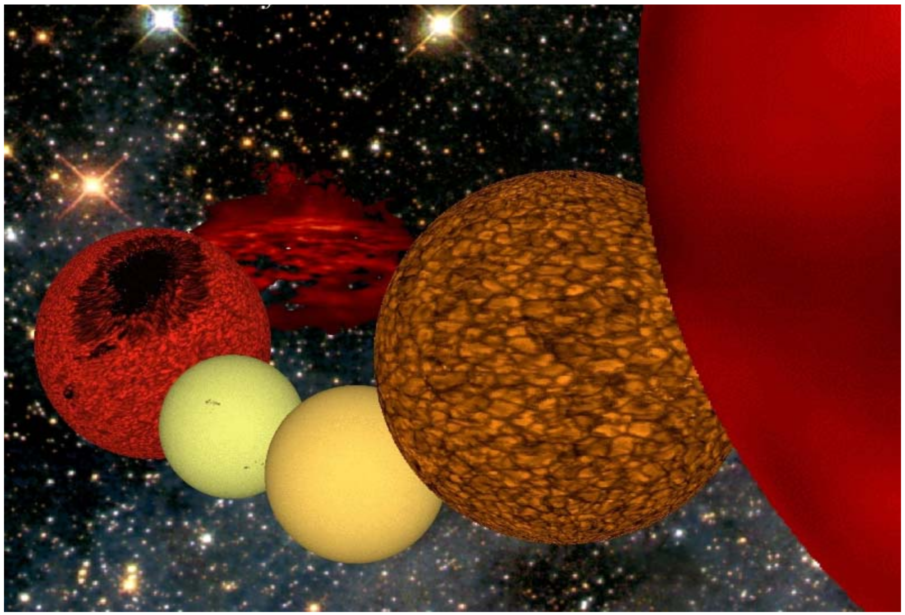
The Stellar Imager (*SI*) "Vision Mission":

A UV/optical observatory for 0.1 milli-arcsec imaging of magnetic field structures that govern:



- **formation of stars & planetary systems**
- **habitability of planets**
- **transport processes on many scales in the Universe**

K. G. Carpenter (NASA/GSFC), C. J. Schrijver (LMATC), M. Karovska (SAO)
and the SI Mission Concept Development Team

URL: http://hires.gsfc.nasa.gov/~si

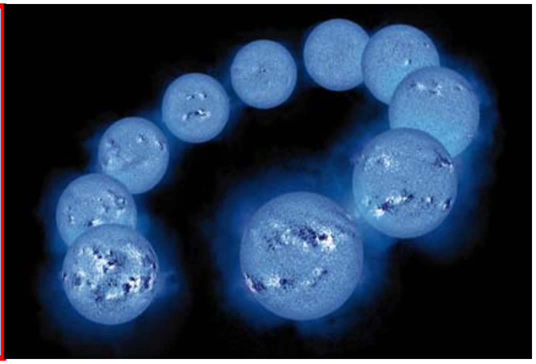
Presented at the Joint Origins/SEU Subcommittees Meeting ,
held November 8-9, 2004, in College Park, MD

Magnetic fields
affect the evolution of structure in the Universe and
drive stellar activity which is key to life's origin and survival

BUT

Our understanding of how magnetic fields form and evolve is currently very limited, even for the nearest star, our Sun.

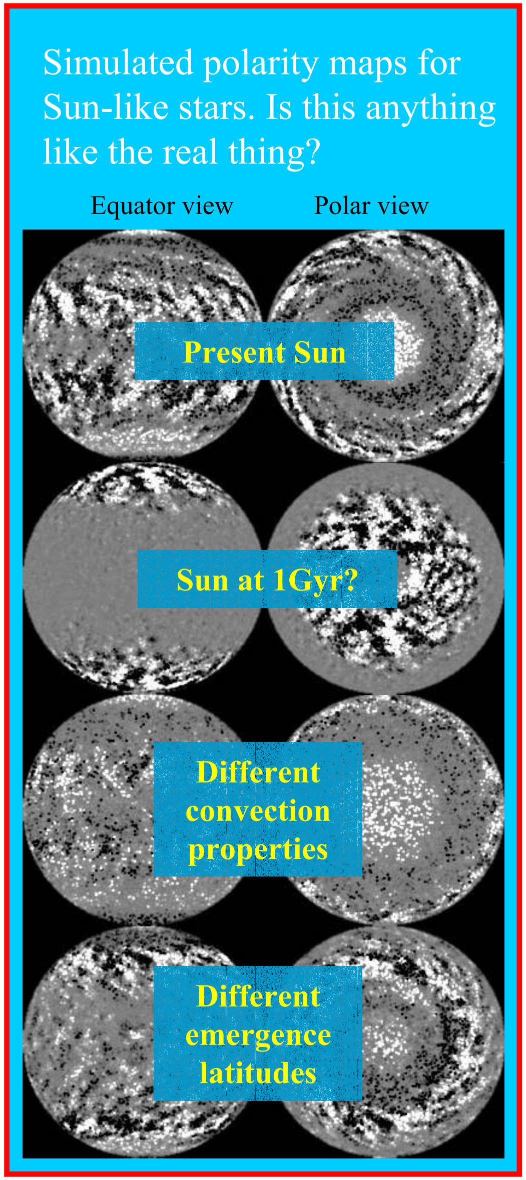
Our close-up look at the Sun has enabled the creation of approximate dynamo models – but none predict the level of magnetic activity of the Sun or any other star.



Major progress in understanding stellar magnetism requires a population study: we need maps of the evolving patterns of magnetic activity, and of subsurface flows, for stars with a broad range of masses, radii, and activity levels.

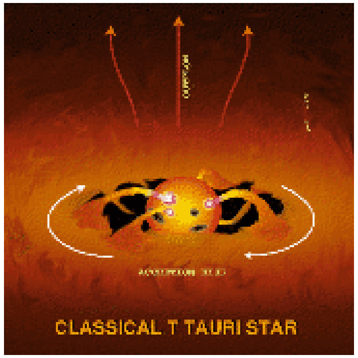
This will provide a major stepping stone toward deciphering magnetic fields and their roles in more exotic, complex, and distant objects.

Solar-type dynamos: a BIG puzzle

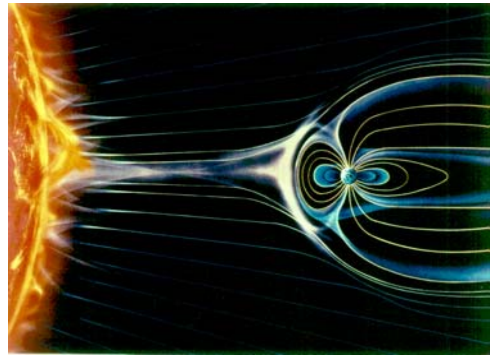


- Solar-type magnetic activity
  - requires convective envelope
  - is strengthened by rotation
  - weakens as rotation slows with age
- We do not know
  - what sets the dynamo strength and pattern
  - how active stars can form polar spots
  - what to expect next from the Sun, on time scales from hours to centuries
  - what causes solar-type ‘Maunder minima’ or ‘grand maxima’
  - why 2 in 3 Sun-like stars show no cycles

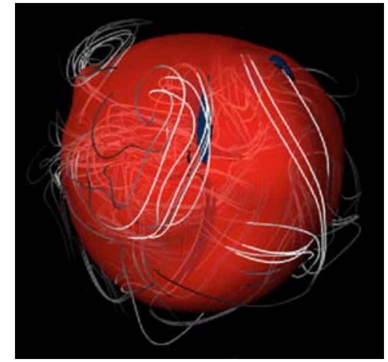
Stellar Magnetic Fields: Key Questions



The cradle of life

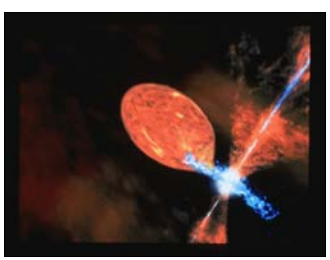


Stellar activity & planets, life

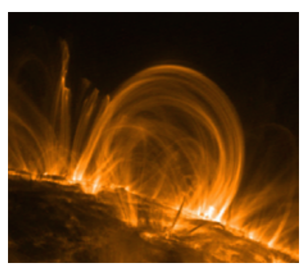


Dying giants

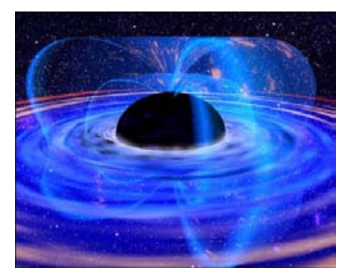
- how does the dynamo evolve?
- how do magnetic fields affect star & planet formation?
- how do fully convective stars sustain magnetic activity?
- how do magnetic fields cause and control jets?
- can we generalize stellar dynamo properties (e.g., close binaries, accretion disks, AGNs, …)?



Interacting binary



The Sun



Accreting AGN

0.1 milli-arcsec UV/optical imaging enables unique studies of magnetic fields and small-scale structures in a wide variety of astronomical sources

Magnetic Processes in Stars
activity and its impact on planetary climates and on the origin and maintenance of life;
stellar structure and evolution

Stellar interiors
in stars outside solar parameters

Infant Stars/Disk systems:
accretion foot-points, magnetic field structure & star/disk interaction

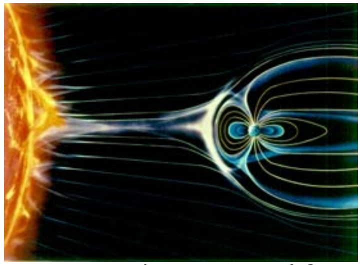
Hot Stars
hot polar winds, non-radial pulsations, envelopes and shells of Be-stars

Cool, Evolved Giant & Supergiant Stars
spatiotemporal structure of extended atmospheres, pulsation, winds, shocks

Supernovae & Planetary Nebulae
close-in spatial structure

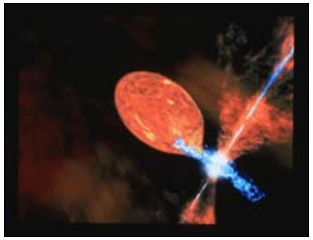
Interacting Binary Systems
resolve mass-exchange, dynamical evolution/accretion, study dynamos

and many other astronomical sources
e.g., Active Galactic Nuclei:
transition zone between Broad and Narrow Line Regions;
origin/orientation of jets; distances

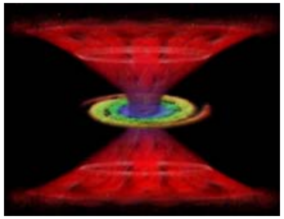


Stars, Planets, Life

Evolved Stars



Interacting Binaries



AGN BELR

Diagnostics for activity and seismology

- The SI prime Science goals require
  - Imaging stellar surfaces to measure flux emergence patterns (in latitude and longitude) and flux dispersal and advection (by convection, differential rotation, and meridional circulation).
  - the use of spatially-resolved asteroseismology to measure large-scale flows on the surface and in the interior.
- which only can be met by high angular-resolution UV/optical imaging (UV for surface imaging, broad-band optical for seismology)

Technique:		**Because:**
Doppler imaging	Fails	Sources evolve well before a rotation is completed on a Sun-like star; latitude ambiguity on fast rotators
Rotational modulation	Fails	Sources evolve too fast; no latitude information; no reference level
X-ray imaging	Fails	No access to asteroseismology; too much confusion by rapid coronal evolution
Optical only imaging	Fails	Works for seismology, but not for surface imaging (Spot coverage too small on Sun-like stars; no access to surface flows as spots dissolve)
UV & optical imaging	**Succeeds**	UV → High contrast to detect active regions and their dispersed patterns; Optical → seismology

The *Stellar Imager (SI)*

is a long-baseline, space-based, UV-optical telescope designed to observe the Universe at ultra-high angular resolution

Summary of Key SI Science Goals

- **Study the evolution of stars and their magnetic dynamos through time**
  - to understand why the Sun varies
  - to enable forecasting of stellar activity on time scales of days to centuries
  - and thereby understand the variable impact of stellar magnetic activity on planetary climates and the origin and maintenance of life
- **Complete the assessment of external solar systems begun with the planet-finding and imaging missions**
  - by imaging the central stars of those systems to determine the impact of their activity on the habitability of the surrounding planets
- **Study the Universe at ultra-high angular resolution to understand**
  - the origin of stars, planetary systems, and life
  - the structure of stars and the life cycle of stars and their planetary systems
  - dynamo and accretion processes, mass-exchange, and mass flows in, e.g., AGN's, black hole environments, supernovae, binary stars, and highly evolved stars

SI and the NASA-ESA Strategies

– *SI* addresses science goals of 3 research Themes in the NASA Science Mission Directorate
    - ***learn how galaxies, stars, planetary systems form & evolve (Origins/EUD)***
    - ***understand development of structure/flows of magnetic fields (SEU/EUD)***
    - ***understand origins & societal impacts of variability in SEC (SSSC/SEED)***
– ***SI*** complements the planetary imaging interferometers
    - ***Terrestrial Planet Finder/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.
– ***SI*** is on the strategic path of NASA Origins interferometry missions
– ***SI*** is a stepping stone towards crucial technology…
    - comparable in complexity to the ***Terrestrial Planet Finder-I***
    - will serve as technological & operational pathfinder for ***Planet Imager***

TPF/Darwin, SI, and ***PI*** together provide complete views of other solar systems

SI Prime Science Requirements

- Study spatial/temporal stellar magnetic patterns in a sample of stars of widely different activity
- images must have resolution elements small enough to separate large active regions and see the field evolve
    - measure: sizes, lifetimes, and emergence patterns of active regions
    - with 30 pixels across a diameter
    - at wavelengths with high contrasts between active & inactive regions
    - imaging every few hours to avoid rotational smearing
    - for up to at least one full rotation period
    - spanning multiple years to investigate pattern changes with time
- Measure internal stellar structure and rotation in a subset of the sample
    - observe low to intermediate degree non-radial seismic modes
- Include the central stars of extrasolar planetary systems in the sample

SI Design Requirements

Requirements for imaging of stellar surface activity

- Obtain ~1000 pixels over a stellar disk to detect & study active regions
- Observe in light of selected UV emission lines (Mg II h&k 2800 Å, C IV 1550 Å) to image transition region/chromospheric plages
  - Plages are bright regions which are larger and have much higher-contrast than dark starspots observable at optical wavelengths
  - UV => 10x smaller baselines (5x larger regions, 2x shorter λ's)
- Image quickly enough to avoid smearing due to rotation, activity evolution, proper motion
  - integration times ~ hours for dwarfs to days for giants

Requirements for study of stellar interiors by seismology

- obtain 30-100 total resolution elements to measure non-radial resonant waves
- with very short integration times
  - minutes for dwarf stars to hours for giant stars
  - requires broadband optical wavelengths to get sufficiently high fluxes

Flexible interferometer configuration required for image synthesis

SI Strawman Mission Concept and Technology Challenges

Mission Concept Development Team

- Mission concept under development by NASA/GSFC in collaboration with experts from industry, universities, & astronomical institutes:

Ball Aerospace & Technologies Corp.
NASA's Jet Propulsion Laboratory
Northrop-Grumman Space Tech.
Sigma Space Corporation
Space Telescope Science Institute
Stanford University
University of Maryland

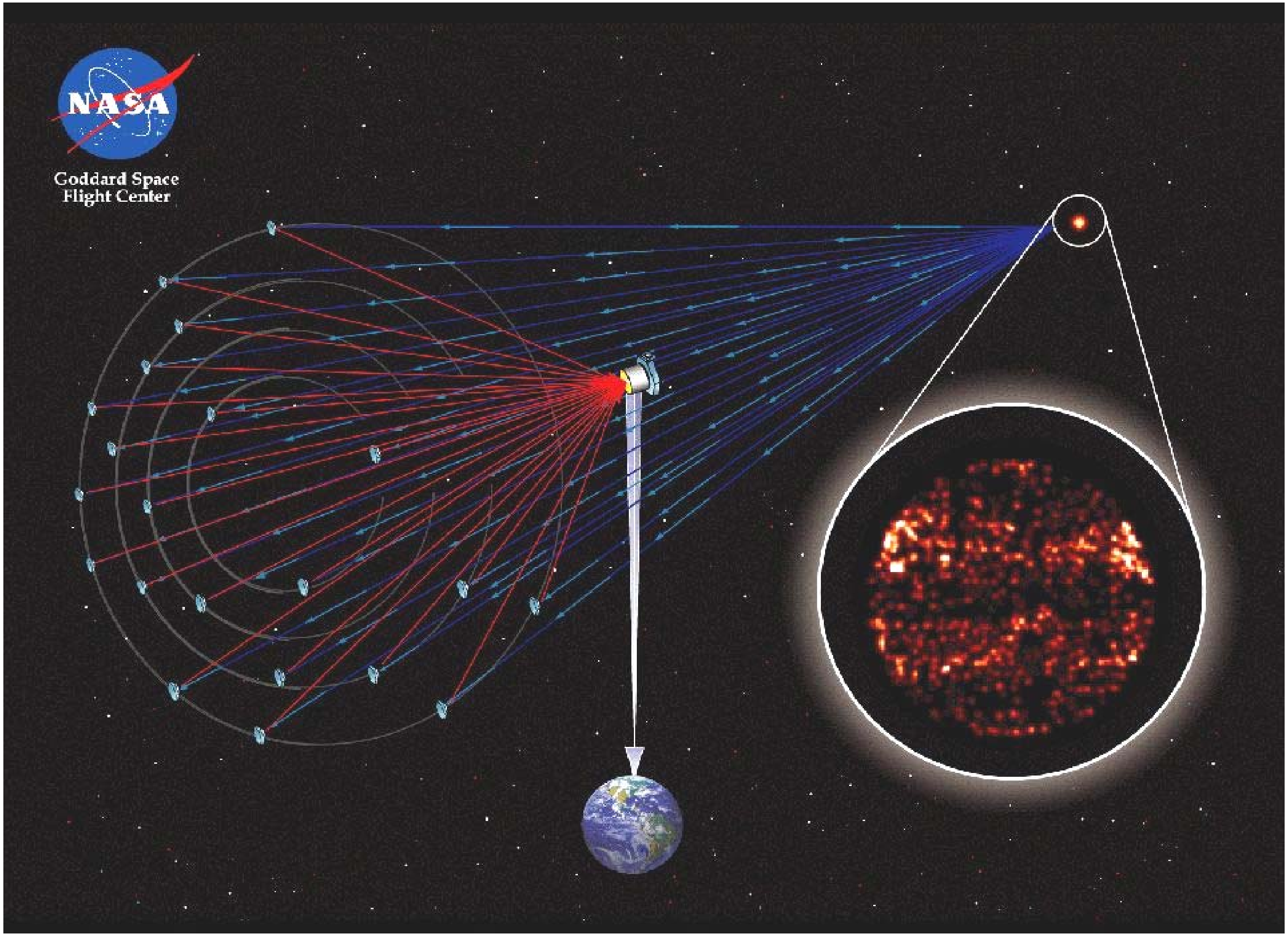
Lockheed Martin Adv. Tech. Center
Naval Research Laboratory/NPOI
Seabrook Engineering
Smithsonian Astrophysical Observatory
State Univ. of New York/Stonybrook
University of Colorado at Boulder
University of Texas/Arlington

European Space Agency
Potsdam Astronomical Institute

Kiepenheuer Institute
University of Aarhus

- Institutional and topical leads from these institutions include:
  - K. Carpenter, C. Schrijver, R. Allen, A. Brown, D. Chenette, D. Mozurkewich, K. Hartman, M. Karovska, S. Kilston, J. Leitner, A. Liu, R. Lyon, J. Marzouk R. Moe, N. Murphy, J. Phillips, F. Walter
- Additional science and technical collaborators from these institutions include:
  - T. Armstrong, T. Ayres, S. Baliunas, C. Bowers, G. Blackwood, J. Breckinridge, F. Bruhweiler, M. Cuntz, W. Danchi, M. Elvis, N. Evans, C. Grady, F. Hadaegh, G. Harper, L. Hartman, P. Kaaret, R. Kimble, S. Korzennik, E. Lorenzini, P. Liewer, R. Linfield, M. Lieber, J. Linsky, M. Marengo, L. Mazzuca, J. Morse, L. Mundy, S. Neff, C. Noecker, R. Reinert, D. Sasselov, E. Schlegel, J. Schou, P. Scherrer, M. Shao, W. Soon, G. Sonneborn, R. Stencel, M. Velli, B. Woodgate, X. Zhang
- International Partners include:
  - J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe

"Strawman" SI Mission Concept



“Strawman” Mission Concept (con’t)

- Design
  - a 0.5 km diameter space-based UV-optical Fizeau Interferometer
  - located near Sun-earth L2 to enable precision formation flying
  - 20-30 primary mirror elements focusing on beam-combining hub
  - large advantages to flying more than 1 hub:
    - critical-path redundancy & major observing efficiency improvements
- Capabilities
  - angular resolution of 0.06 & 0.12 milli-arcsec at 1550 & 2800 Å
  - ~1000 pixels of resolution over the surface of nearby dwarf stars
  - observations in
    - ~10-Ångstrom UV pass bands
      - C IV (100,000 K)
      - Mg II h&k (10,000 K)
    - broadband, near-UV or optical continuum (3,000-10,000 K)
  - a long-term (> 10 year) mission to study stellar activity cycles:
    - individual telescopes/hub(s) can be refurbished or replaced

Simulated SI Images (1550 Å) for Various #Mirrors/Rotations

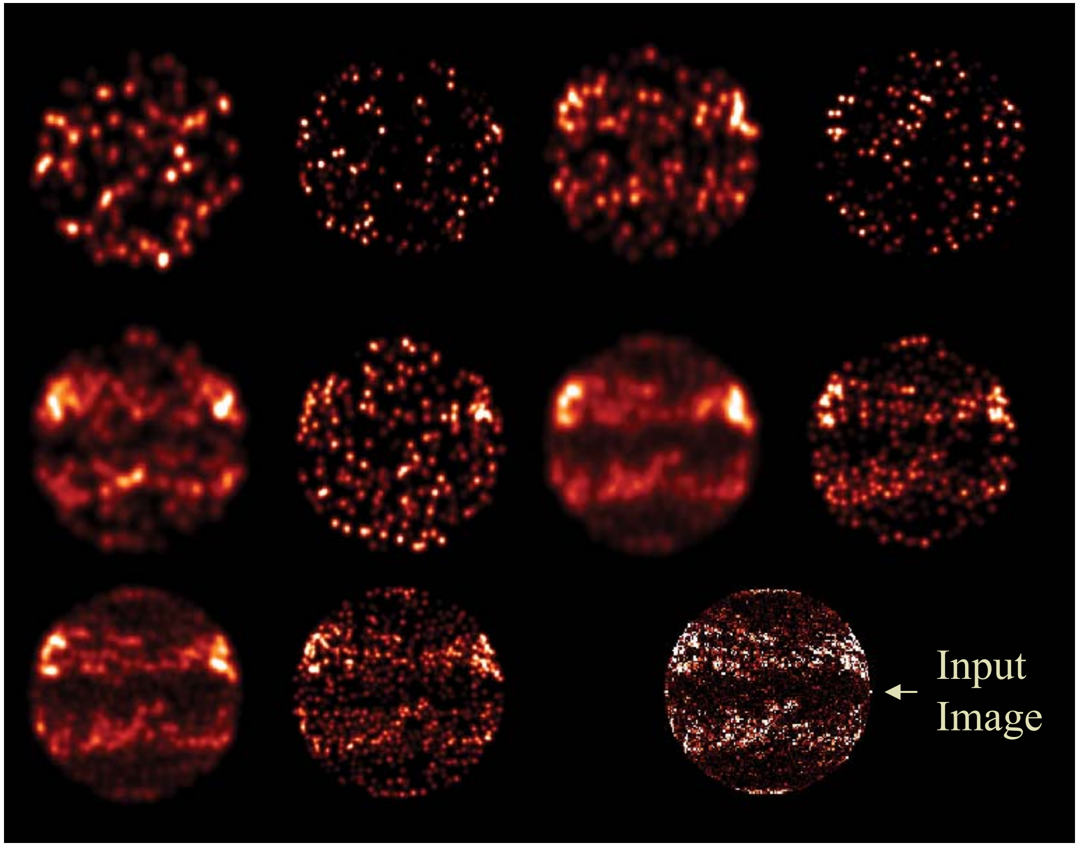
“Snapshots” (no rotations) (24 array rotations)

elements (layout)

6 (Y-array)

12 (Y-array)

30 (Golomb Rectangle)



Baselines: 250 m 500 m 250 m 500 m

Simulations calculated using SISIM, written by R. Allen/J. Rajagopal, STScI

Top Technological Challenges and Enabling Technologies

- formation-flying of ~ 30 spacecraft
  - deployment and initial positioning of elements in large formations
  - aspect control to 10's of micro-arcsec
  - positioning mirror surfaces to 2 nm
  - ultra-high stability over exposure time
- precision metrology (2 nm over multi-km baselines)
  - multiple modes to cover wide dynamic range
- wavefront sensing and real-time, autonomous analysis
- real-time correction and control of formation elements
  - staged-control system (km → cm → nm)
- methodologies for ground-based validation of distributed systems

Tentative Schedule

2005: Complete Vision Mission Study

2005-08: Continue studies of multi-element fine optical control with Fizeau Interferometer Testbed (FIT) and Staged-Control Testbed (SCT), contingent on funding

2005->: Continue other technology development efforts, including precision formation flying, micro-newton level thrusters, wavefront sensing and control, methodologies for integration and test of large distributed system

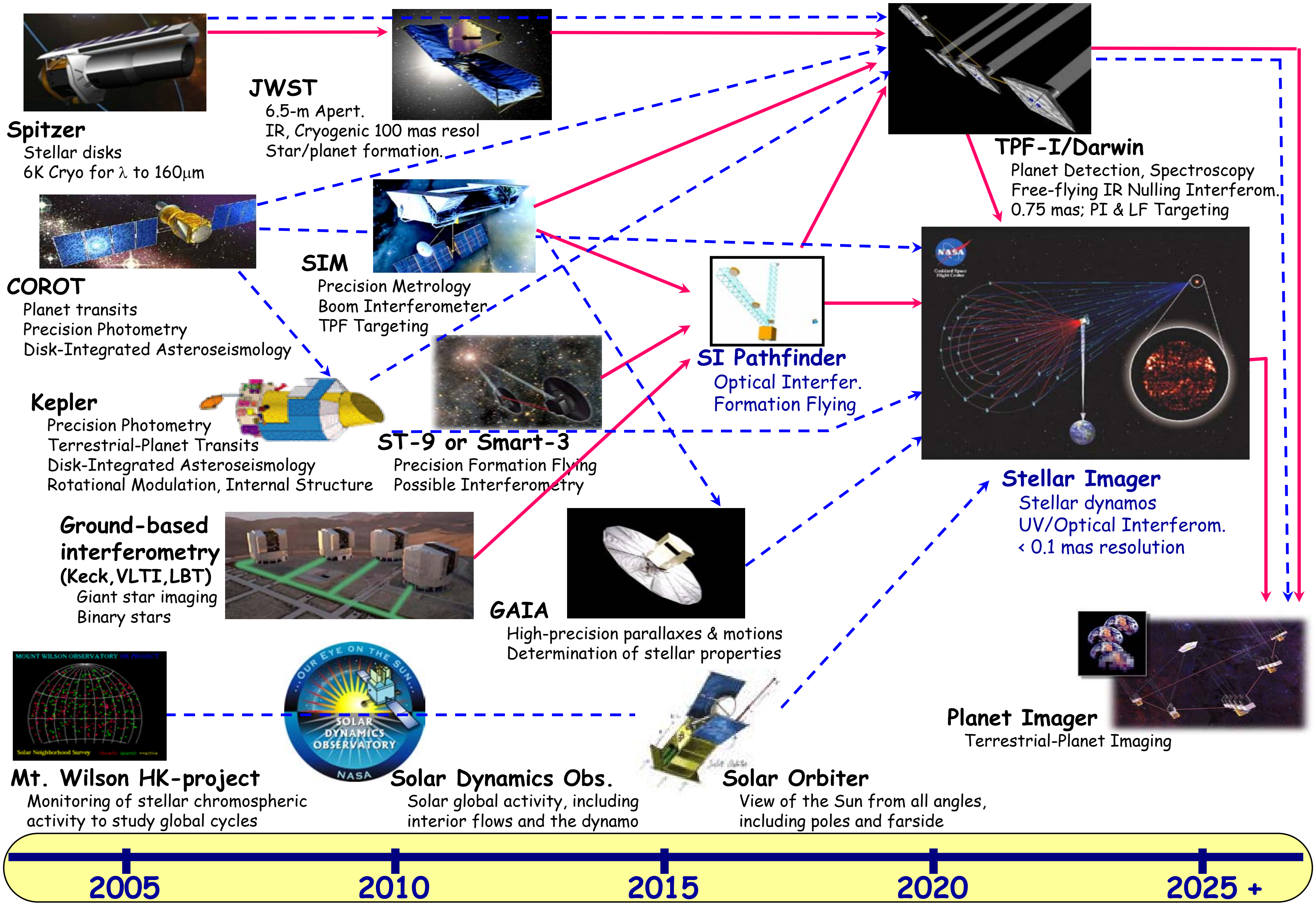
2006: Develop Pathfinder Concept suitable for "Origins Probe" type opportunity

2007: Propose Pathfinder Mission

2015: Fly pathfinder mission

2024: Fly full mission

Science and Technology Interdependencies of SI and other Missions



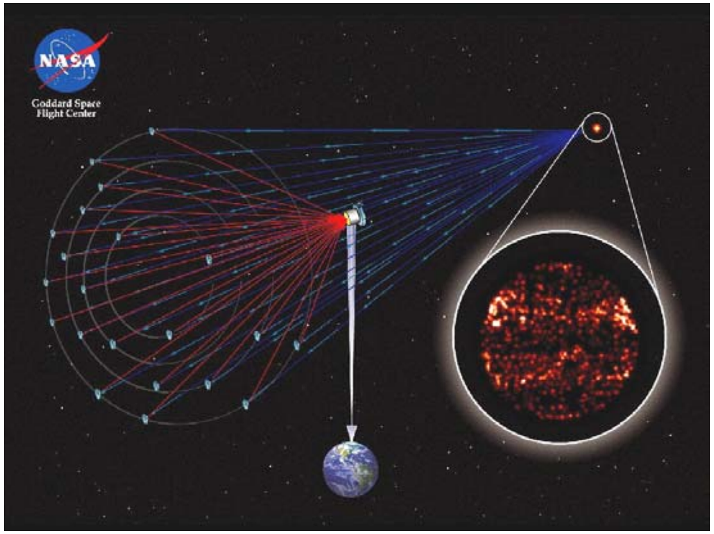
SI Status

- SI in NASA SEC (now SSSC) Roadmap
- SI selected for further concept development by the NASA HQ 2003 Vision Mission NRA review
- Major Partnerships established with LMATC, BATC, NGST, JPL, SAO, CU to develop concept/technology
- Phase I of the Fizeau Interferometry Testbed (FIT) has begun operation to develop closed-loop optical control of a multi-element array
- GSFC Integrated Mission Design Center (IMDC) study executed in October, 2004 to produce a system design and a technology development roadmap.

For more information, see: **http://hires.gsfc.nasa.gov/~si**

Summary: Stellar Imager (SI) Vision Mission

- UV-Optical Interferometer to provide 0.1 mas imaging of
  - magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, transport processes on many scales in the Universe
- 20-30 “mirrorsats” formation-flying with beam combining hub
- Launch ~ 2024, to Sun-earth L_2
- maximum baseline ~500 m
- => 1000 pixels/stellar image
- Mission duration: 10 years



http://hires.gsfc.nasa.gov/~si

Prime Science Goals

image surface/sub-surface features of distant stars; measure their spatial/temporal variations to understand the underlying dynamo process(es)

enable improved forecasting of solar/stellar activity on time scales of days to centuries

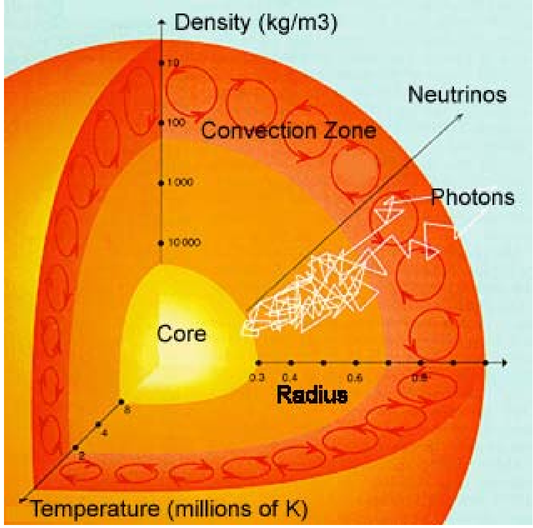
understand the impact of stellar magnetic activity on planetary climates and life

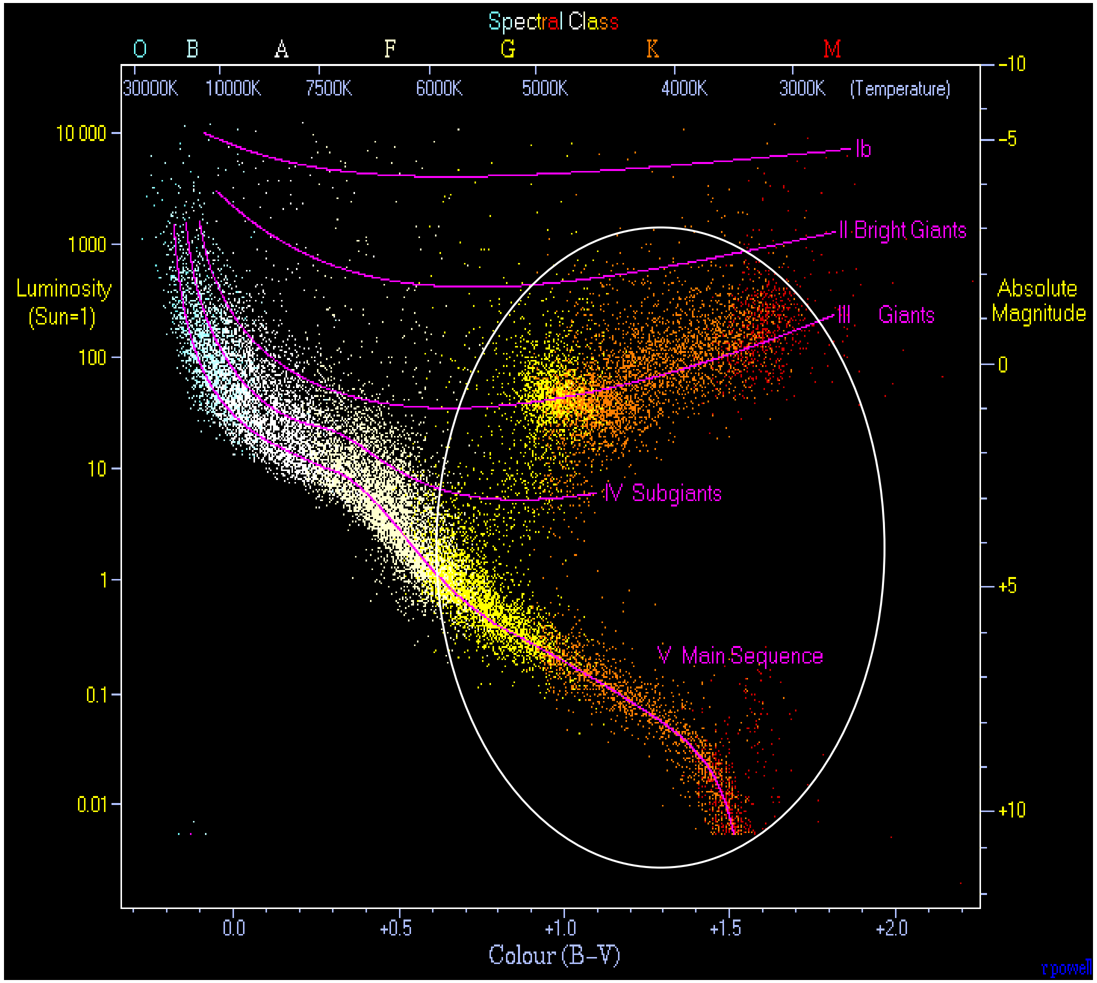
complete the assessment of extrasolar planetary systems found by SIM/TPF, etc.

Additional Science Goals: high resolution studies of Active Galactic Nuclei, Quasars, Supernovae, Interacting Binary Stars, Forming Stars/Disks

Appendix: Supplemental Information

Solar-like activity

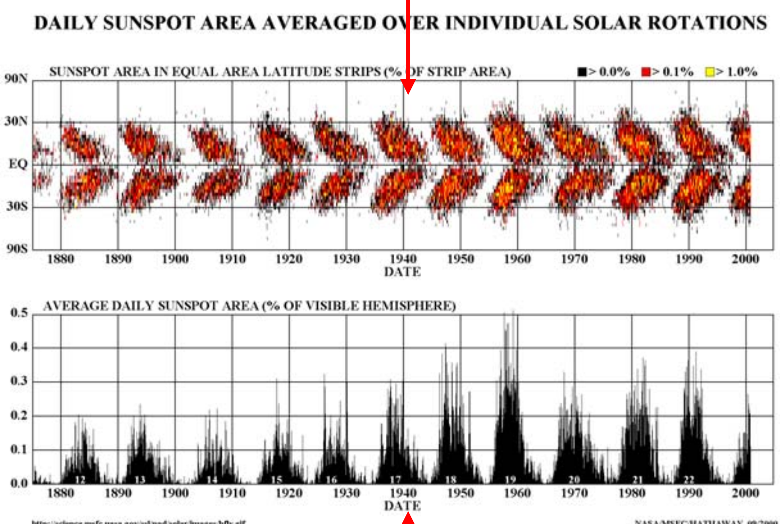




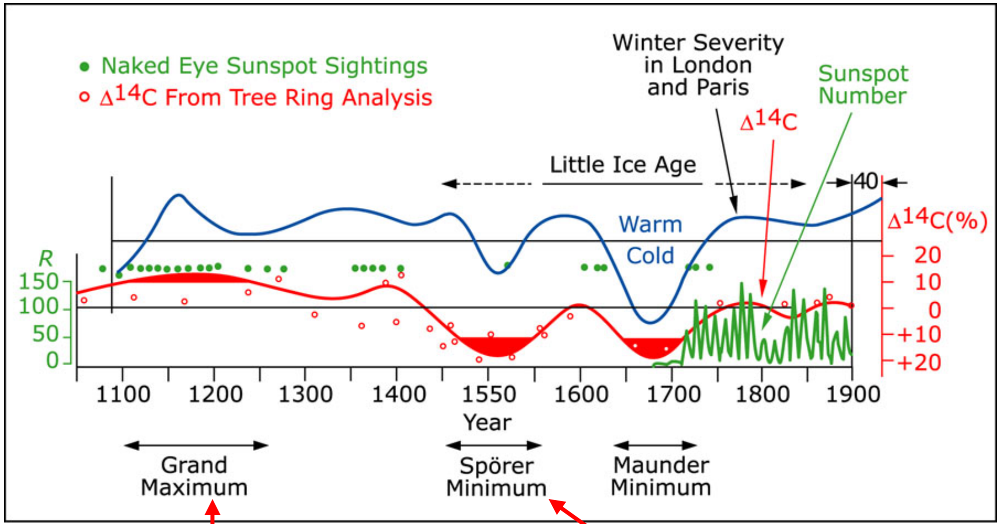
All stars with convective shells exhibit solar-like atmospheric magnetic activity; rotation strengthens activity.

Solar Variations & Effects on Earth

The Solar Activity "Pattern" –
The "Butterfly Diagram"
(latitude/longitude vs. time)



sunspots vs. time

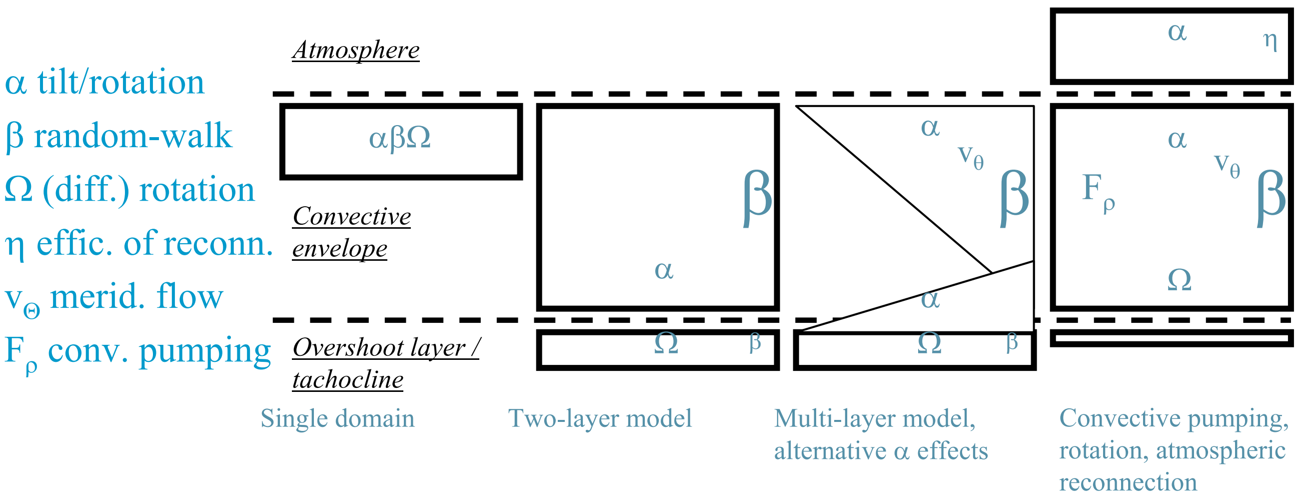


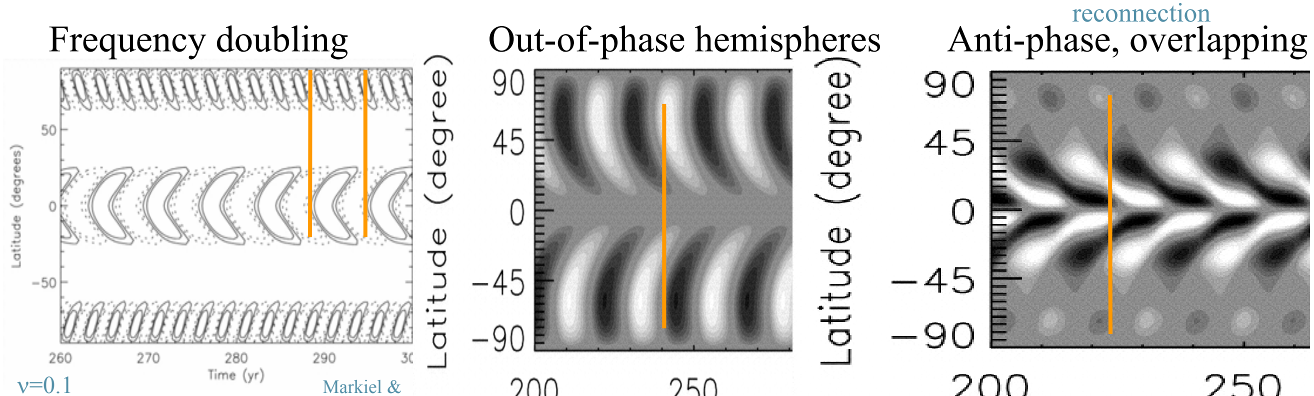
"global warming",
aggravating greenhouse effect

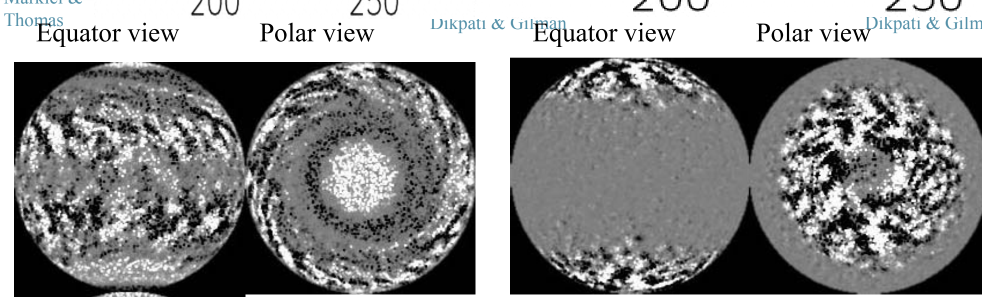
crop failures,
July skating on the Thames

short-term effects:
disable satellites & power grids,
increase pipeline corrosion, endanger
astronauts

Testing models for stellar magnetism







Sun-like source and transport High-lat emergence, strong flows

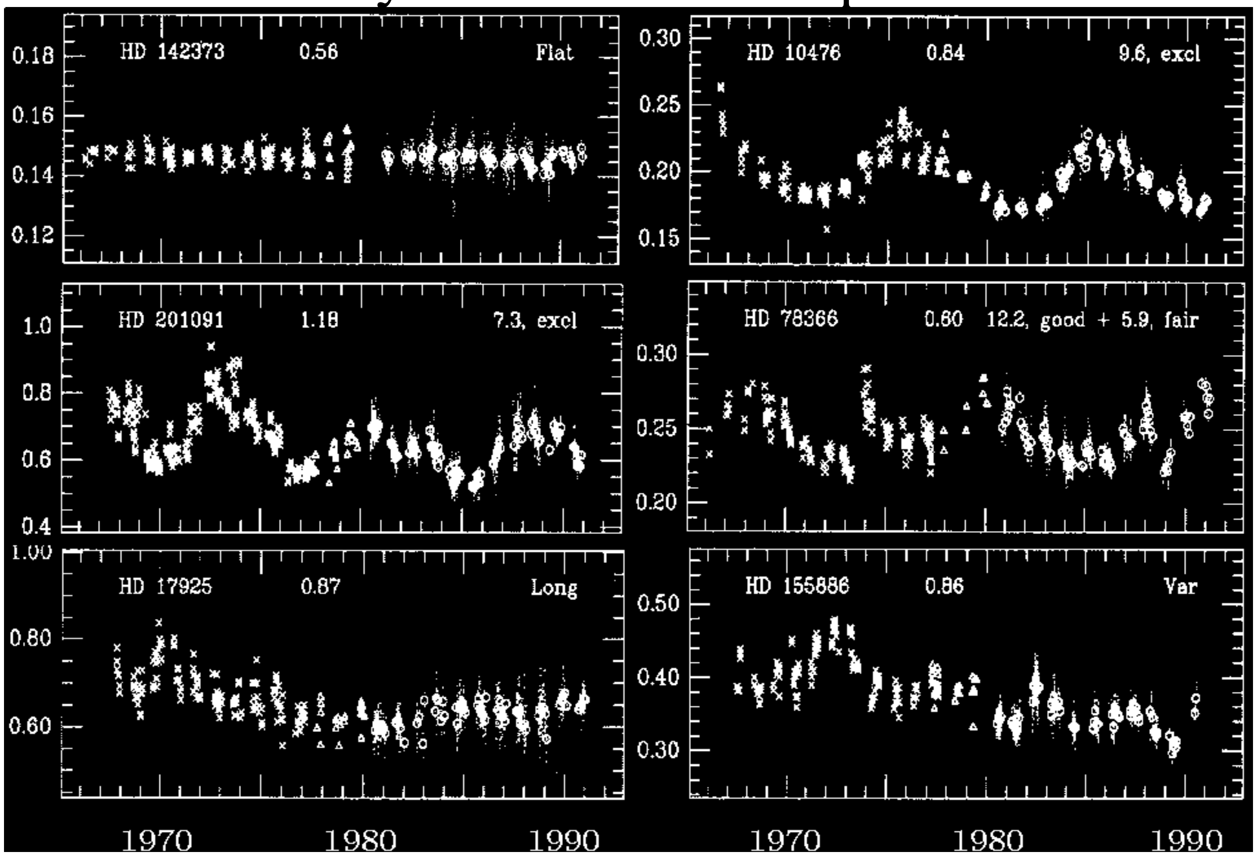
Ingredients:
Dynamo models include a variety of severely simplified processes, functioning or interacting in different domains of interior and atmosphere

Flux emergence:
Patterns of emerging flux depend sensitively on model processes and parameters, resulting in a variety of 'butterfly diagrams'

Surface transport:
Surface activity patterns depend both on the flux emergence pattern and on the flux dispersal and transport processes.

Stellar activity patterns

A sampling of patterns of chromospheric activity in a variety of cool main-sequence stars:



F8 V
Slightly warmer than the Sun

K1 V
Sun-like cycle, but much cooler

K5 V
0.7 solar radii

F9 V
Slightly warmer than the Sun

K2 V
Long cycle?

K0 V
Irregular or multi-periodic?

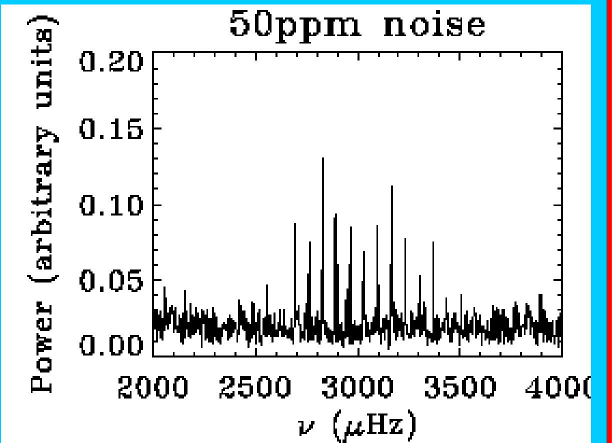
Only 1 in 3 Sun-like stars exhibit regular cycles.
We have no idea why!

The Value of Spatially-Resolved Asteroseismology

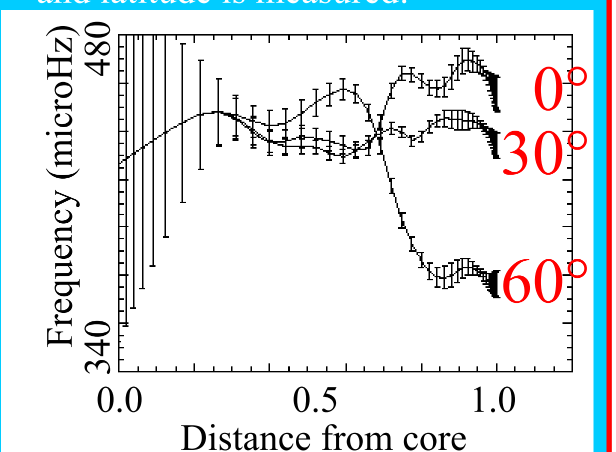
– Stellar dynamo: internal rotation
  - Radial rotation profile in radiative interior and fairly deep layers of the convective envelope.
  - Latitude variation of near-surface rotation.
  - Measurement of properties of stellar tachoclines, presumed to be the seat of the global stellar dynamo.

– Physical quantities and transport mechanisms: internal structure
  - Measure the internal structure for the radiative interior
  - Unambiguously determine stellar ages.
  - Improve knowledge of stellar mixing processes (involving also magnetism) and gravitational settling; these uncertain factors in stellar modeling impact, e.g., Big Bang nucleosynthesis (primordial Li abundance), properties of supernova progenitors (distance scale, and stellar abundance yields into galaxies).
  - Measure the equation of state and test opacities, improving the accuracy of the distance scale of the universe, and the initial He abundance (impacts galactic chemical evolution).

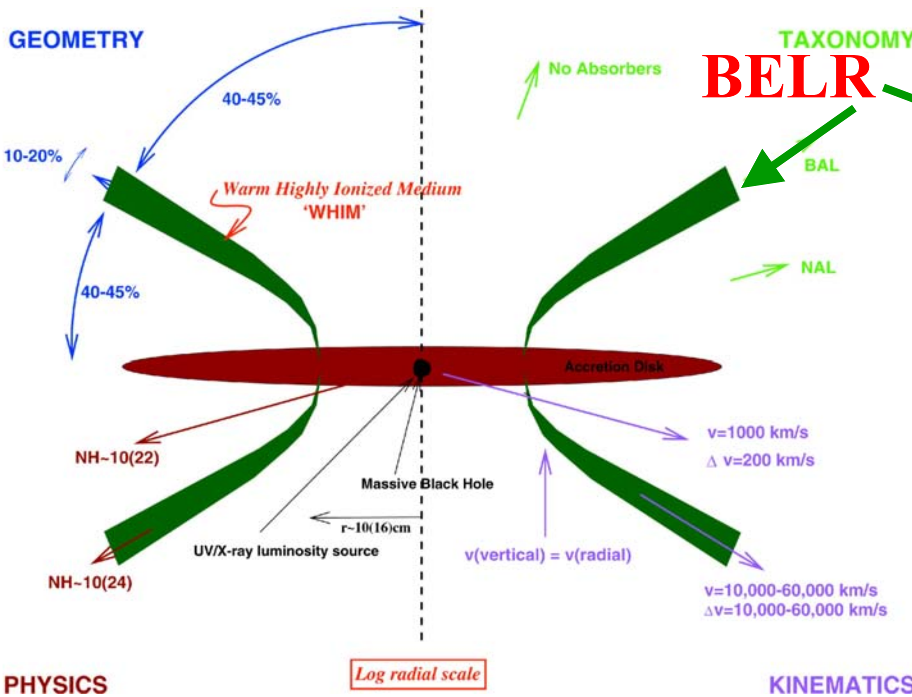
With need only 40 pixels across the star to measure modes up to l=60, so that after one month on target:

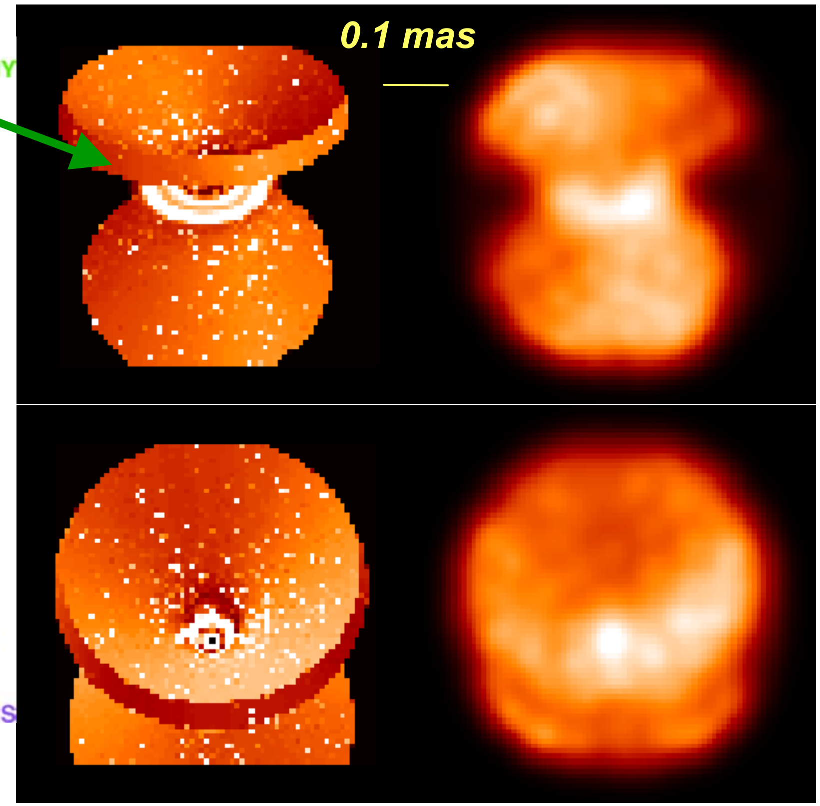


This simulation shows how well a Sun-like rotation profile with depth and latitude is measured:



SI *CIV* line imaging of AGN Broad Emission Line Regions (BELR) differentiates between possible quasar/AGN geometries and inclinations





Model of quasar & AGN outflow geometry

Elvis, 2000

model **SI *SISIM* simulations**

SI Design Reference Mission (DRM)

- Developed a program to produce SI DRM's under various assumptions to enable us to estimate resource needs and observatory capabilities over it's lifetime for various assumptions
- Use of this tool has demonstrated that there are sufficient available science targets to produce an efficient observing program with tolerable # of slews, slew lengths, and desired observing cadences and reasonable demands upon resources (e.g. propellent)
- Assumptions
  - SI will point within 20 deg of the great circle perpendicular to the Sun-SI line (70<beta<110 deg)
  - SI will slew with constant acceleration ➔ slew time ~ sqrt(slew distance)
  - Max slew rate = 10 deg/hr
  - 1 hour overhead to settle on and acquire new target
- Input parameters
  - Targets
    - High priority targets: 20 stars, 50% observed daily for a month
    - Additional targets: ~50 including, e.g., non-solar type stars, AGN's with 1-10 observations/month
    - Extended list of Solar-like & planet-harboring stars: ~350 stars to provide scheduling flexibility, observed with longer cadences
  - Slew rates, Beta limits, Mission start date, Overhead time, Initial SI pointing
- Typical observing efficiency ~ 50%

For Reference--SI Requirements Flow Down (11/03/04)

Science Goals

Understand the dynamo process responsible for magnetic activity in stars

Enable improved forecasting of solar/stellar magnetic activity on time scales of days to centuries

Understand the impact of stellar magnetic activity on planetary climates and on the origin and continued existence of life

Complete the assessment of external solar systems begun with the Planet Finding and Imaging missions by imaging the central stars and determining the impact of the activity of those stars on the habitability of the surrounding planets

Study the Universe (AGN's, QSO's, Black Holes, Super-novae, Interacting Binary Stars, hot stellar winds/non-radial pulsations, forming-stars and disks, cool evolved and long-period variable stars) at high angular/spatial resolution

→

Data Required

Empirical constraints to refine dynamo models. Specifically, for a solar-type star at 4 pc:

Observations of spatial and temporal stellar surface magnetic activity patterns in a sample of stars covering a broad range of activity level:

- UV (1550 Å, 2800 Å) images with 1000 total resolution elements taken with modest integration times (~hours for dwarfs to days for giants)

Measurement of internal stellar structure and rotation:

- Astereoseismology via optical images with 30-100 total resolution elements over a stellar disk to measure non-radial resonant waves with short integration times minutes (dwarfs) to hours (giants)

Long-mission lifetime (>10 years) needed to provide observations over significant fraction of stellar activity cycles

→

Measurement Capabilities

Angular Resolution
  0.1 mas
Spectral Range
  1500 - 6000 Å
Field of View
  ~ 4 mas
Flux Threshold at 1550 Å
  1×10^{-13} ergs/cm^2/s
Observations
  several dozen solar-type stars observed repeatedly over mission lifetime

  month-long seismology campaigns on select targets

↓

Engineering Implications

Baselines from 100 to 500 m

>20 primary optical elements of > 1 m in diameter with UV quality smoothness

Fizeau Beam combination

Path Length Control to 3 nm

Aspect Control to 30 μarcsec

Orientation
  +/- 20deg to orthogonal to Sun

→

Key Technologies

precision metrology and formation-flying

wavefront sensing and closed-loop control of many-element optical systems

deployment/initial positioning of elements in large arrays

metrology/autonomous nm-level control of many-element formations over kms

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)

methodologies for ground-based integration and test of distributed s/c systems

mass-production of "mirrorsat" spacecraft

Precursor/Pathfinder Mission

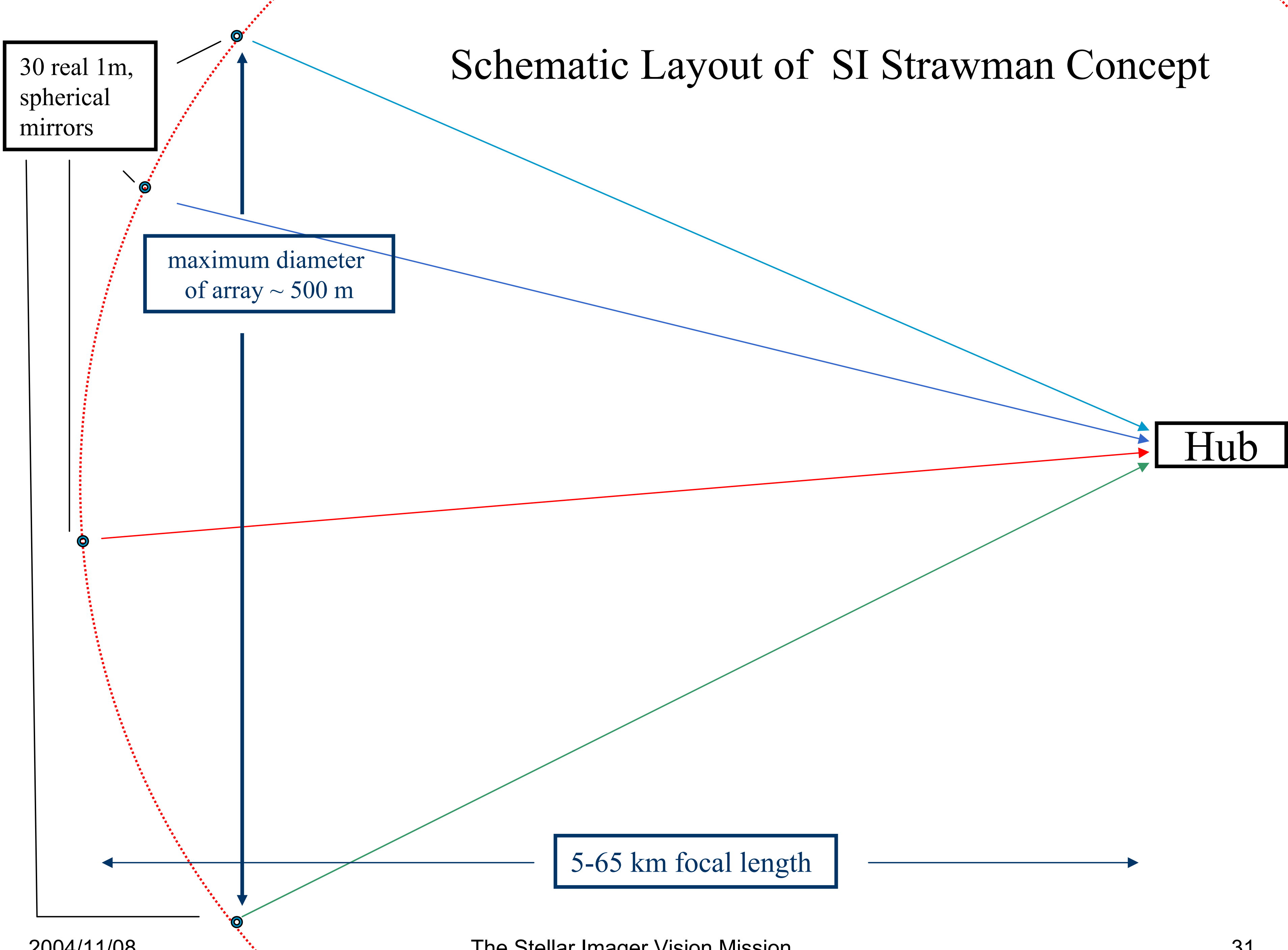
- A pathfinder mission which takes smaller technological steps is desirable to reduce mission risk and would
  - advance technologies needed for other missions in NASA strategic plans
  - will address a subset of the SI science goals

Desirable characteristics of a pathfinder mission

- possible within a decade
- uses a modest number of free-flying spacecraft (3-5)
- operates with modest baselines (~ 50 m)
- performs beam combination with ultraviolet light
- produces UV images via imaging interferometry and enable significant new science

- Such a mission with a small # of spacecraft
  - requires frequent reconfigurations and limits observations to targets whose variability does not preclude long integrations
  - tests most of the technologies needed for the full-size array

Schematic Layout of SI Strawman Concept



Alternative Architectures (Recent IMDC Study)

- Three designs are being examined by the SI Vision Team
- All utilize a large array of primary mirrors (~30) which send light to a beam-combining hub
- Differences are in how the beams are combined and mostly effect hub design, not overall architecture
  - Classical Fizeau with large focal-plane detectors
  - Hybrid Hypertelescope which accepts partial pupil densification in order to maintain use of non-redundant array
  - Fizeau design with remapping of beams from 2D to 1D non-redundant array
- Trades involve system sensitivity, spectroscopic capabilities, and path-length maintenance requirements
- There may be large advantages to flying more than 1 hub: both critical-path redundancy and major observing efficiency improvements (additional hubs can be pre-positioned for next segment of observing schedule, while observations being acquired with first hub)

Additional Challenges and Enabling Technologies

- variable, non-condensing, continuous micro-Newton thrusters
- mass-production of “mirrorsat” spacecraft: cost-effective, high-volume fabrication, integration, & test
- long mission lifetime requirement
- light-weight UV quality spherical mirrors with km-long radii of curvature
- larger format energy resolving detectors with finer energy resolution (R=100)

Stellar Imager and the President's Vision

SI fits into the President's Exploration Initiative in 2 distinct arenas:

1) as one of the "deep-space observatories" which will be a part of the search for and study of habitable planets around other stars.

> Stellar Imager (SI) is an essential part of this mandate since it enables the assessment of the impact of stellar magnetic activity on the habitability of planets found by the planet search and imaging missions (e.g., TPF and Planet Imager (PI)).

2) as a means to improve our ability to forecast space weather within our own solar system:

> Exploration requires that we know space weather throughout much of the heliosphere, and that means we need long-term forecasts of solar activity, which in turn requires a fundamental understanding of the solar dynamo and of all related transport processes. The Living With a Star initiative addresses that on the fairly short term, while the Stellar Imager is to provide the knowledge (constraints from a broad population of stars of differing activity level) critically needed to test and validate models developed under the LWS program.