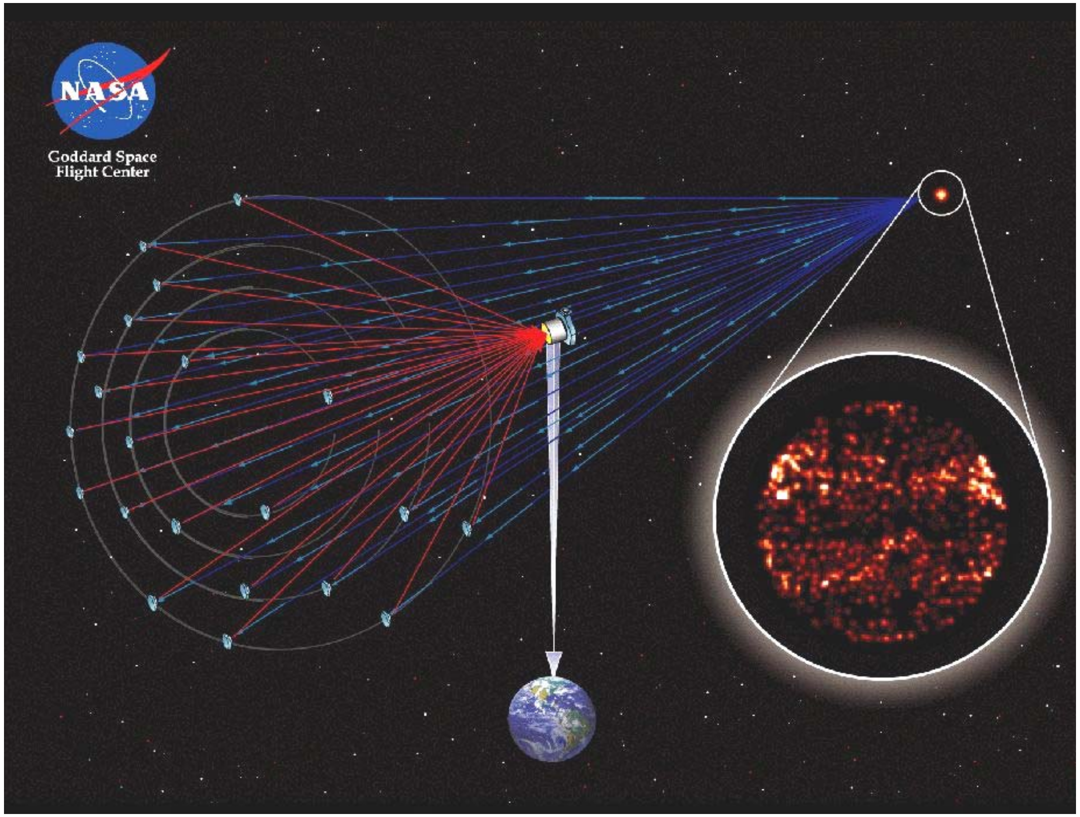
The Stellar Imager (*SI*) "Vision Mission":

Imaging the UV/Optical Universe with Sub-milliarcsecond Resolution



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 MSFC on July 15, 2005

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

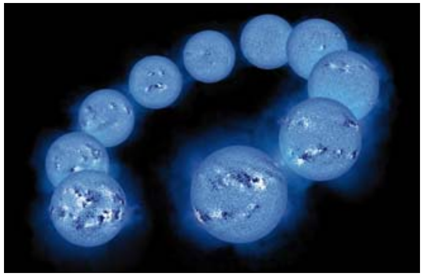
  European Space Agency
  Potsdam Astronomical Institute
  Kiepenheuer Institute
  University of Aarhus

- 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, S. Cranmer, M. Cuntz, W. Danchi, A. Dupree, M. Elvis, N. Evans, C. Grady, F. Hadaegh, G. Harper, L. Hartman, R. Kimble, S. Korzennik, P. Liewer, R. Linfield, M. Lieber, J. Linsky, M. Marengo, L. Mazzuca, J. Morse, L. Mundy, S. Neff, C. Noecker, R. Reinert, R. Reasenberg, D. Sasselov, E. Schlegel, J. Schou, P. Scherrer, M. Shao, W. Soon, G. Sonneborn, R. Stencel, B. Woodgate

- International Partners include:
  - J. Christensen-Dalsgaard, F. Favata, K. Strassmeier, O. Von der Luehe

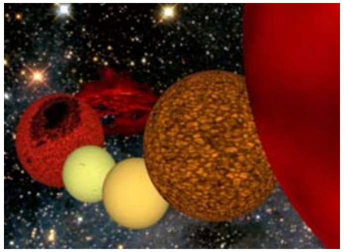
Why Stellar Imager?

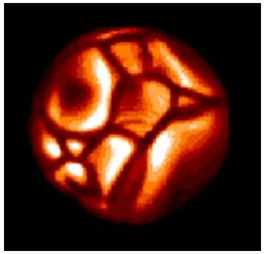


- **Magnetic fields**
  - affect the evolution of structure in the Universe and
  - drive stellar activity which is key to life's origin and survival
- **But our understanding of how magnetic fields form and evolve is currently very limited**
  - Our close-up look at the Sun has enabled the creation of approximate dynamo models, but none predict the level of magnetic activity of the Sun or any other star
- **Major progress requires understanding stellar magnetism in general and that 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 understanding will, in turn, provide a major stepping stone toward deciphering magnetic fields and their roles in more exotic, complex, and distant objects**

Key SI Science Goals

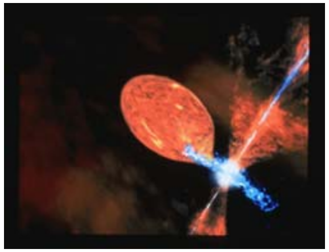
- **Study the evolution of stars & their magnetic dynamos by resolving patterns of surface activity & internal structures & flows in a diverse sample of stars**
  - to improve long-term forecasting of solar & stellar activity and understand the impact of stellar magnetic activity on planetary climates and the origin & maintenance of life
  - to understand the variable Sun-Earth system
- **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
  - internal transport processes in stars at different ages, their impact on stellar evolution, and their consequences for the chemical evolution of galaxies
  - dynamo and accretion processes, mass-exchange, and mass flows in, e.g., AGN's, black hole environments, supernovae, binary stars, and highly evolved stars



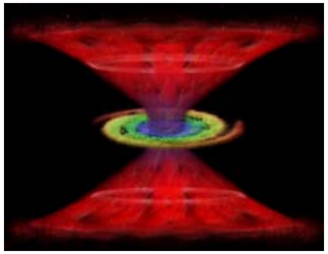


Evolution of Stars, Planets, Life

Supernovae

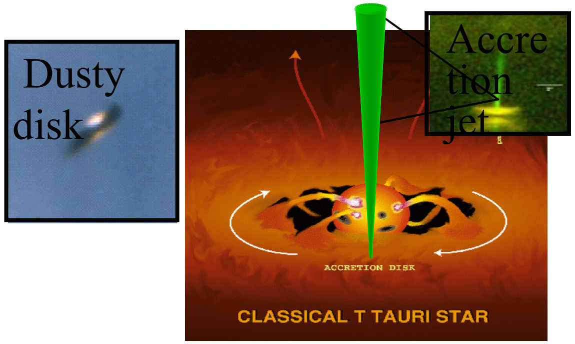


Accretion Jets



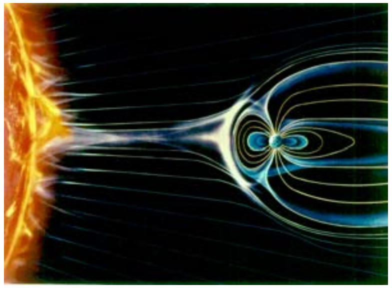
AGN BELR

Science Driver: Stellar Activity is Key to Understanding Life in the Universe and Earth's habitability

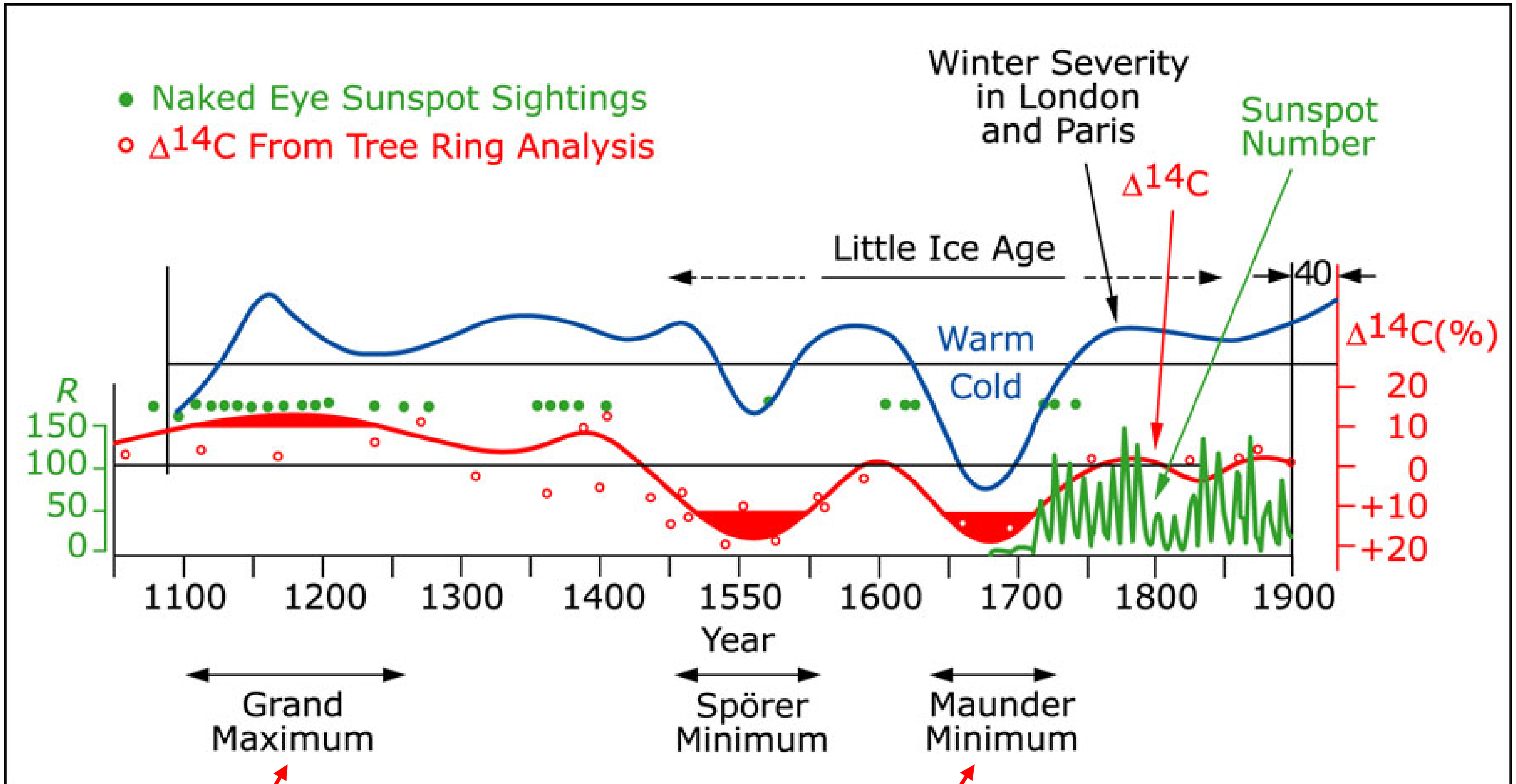


The stellar magnetic field

- 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



Effects of Solar Variations



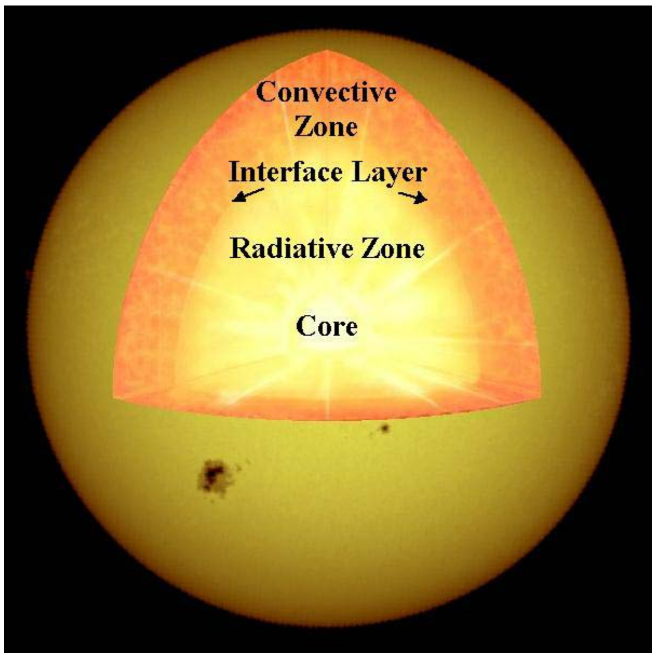
“global warming”,
aggravating greenhouse effect

crop failures,
July skating on the Thames

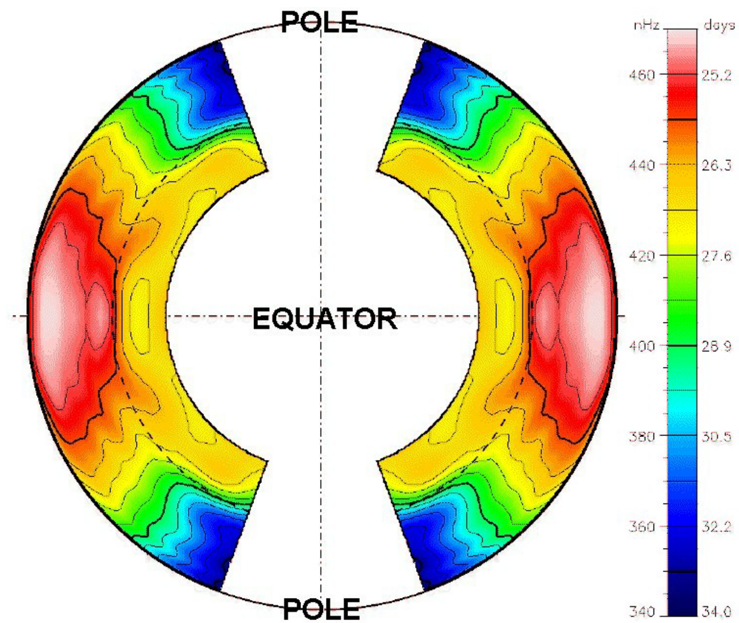
short-term effects:
disable satellites & power grids,
increase pipeline corrosion,
endanger astronauts

The Convection Zone

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

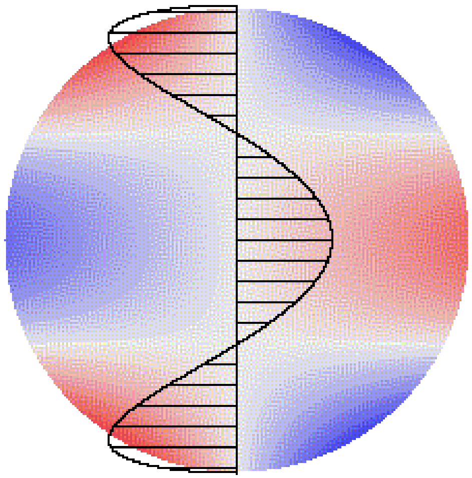


Radial Structure of Sun

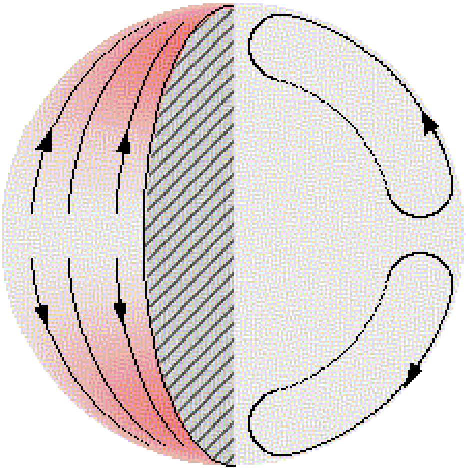


Internal rotation rate of sun

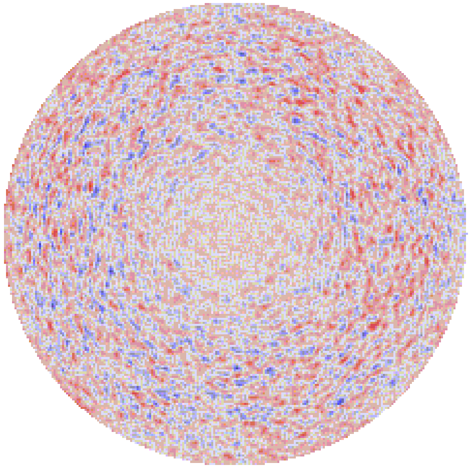
Flows on the Sun



Differential Rotation

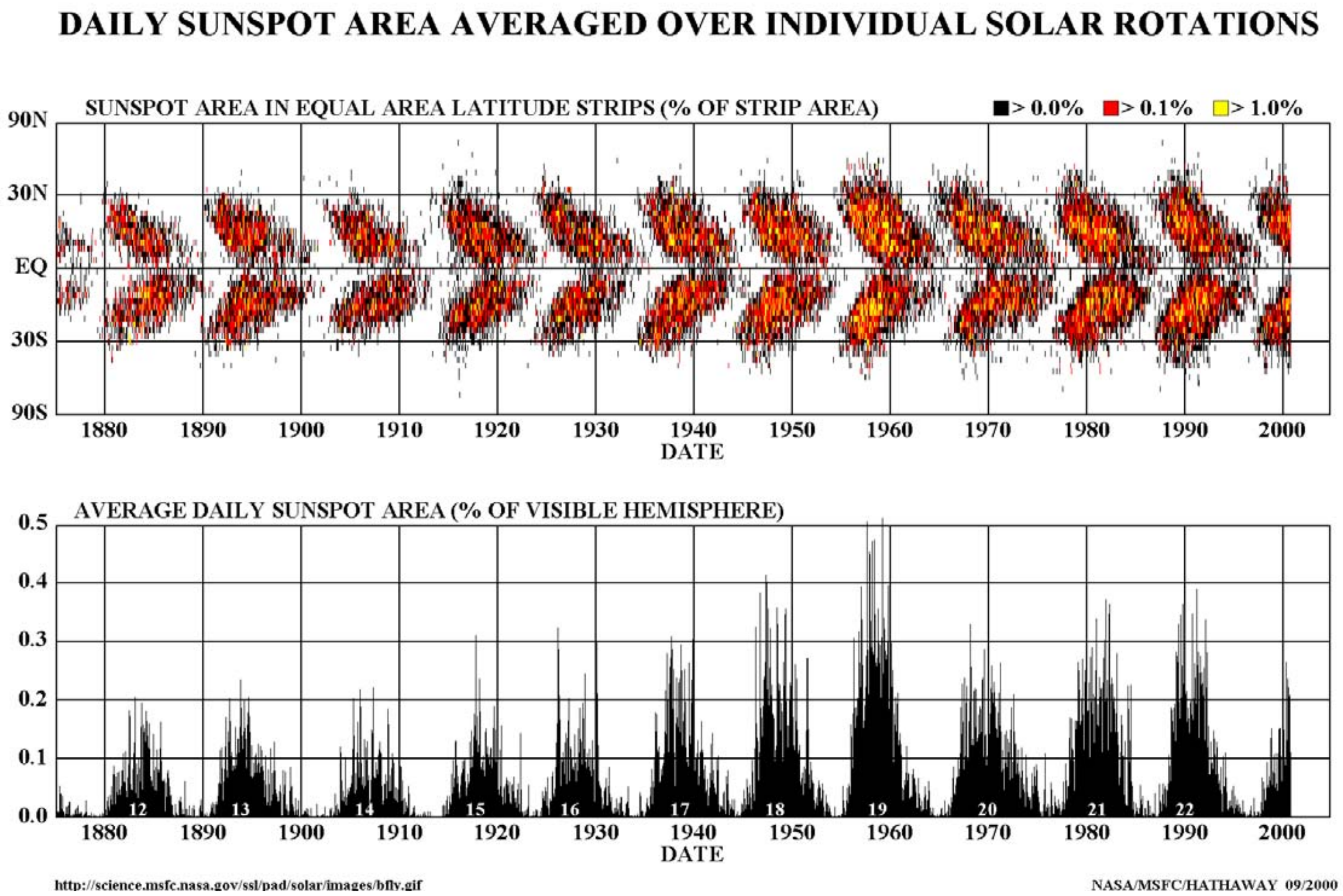


Meridional Flow



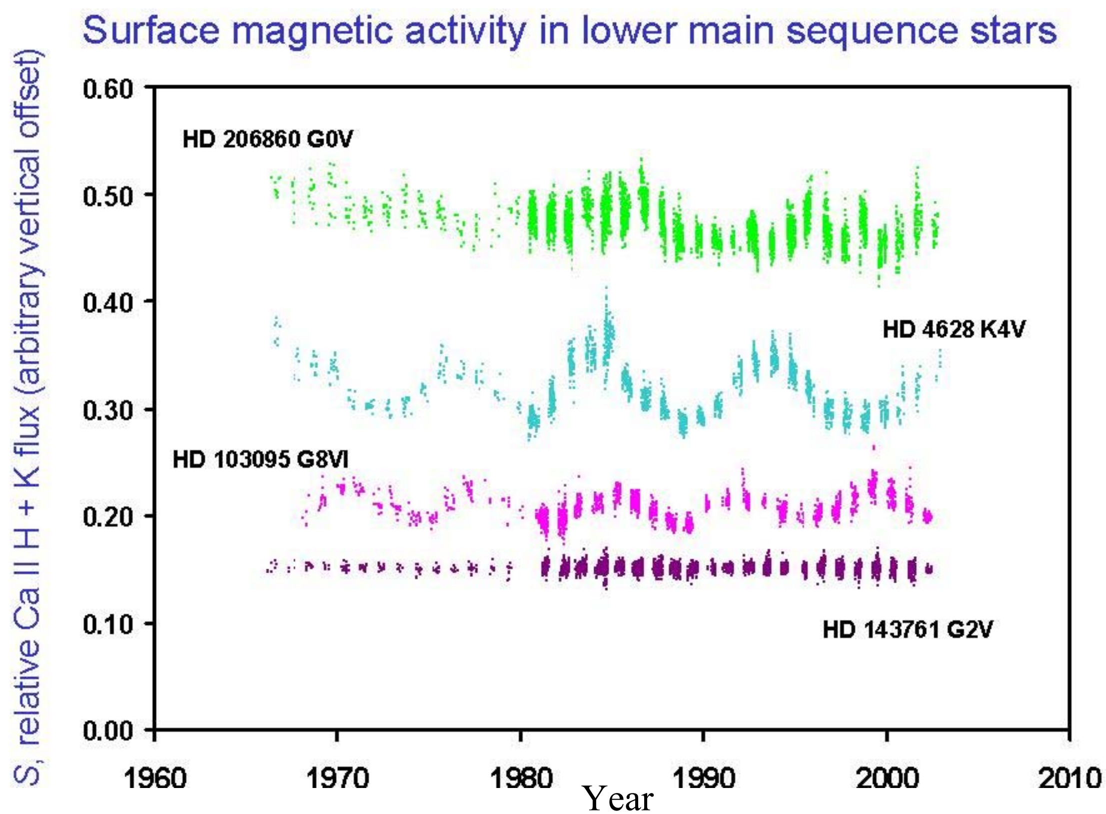
Convective Supergranulation

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



Temporal Patterns of Stellar Activity I.

- Disk-Integrated Ca II Light shows cycles (Mt. Wilson Program)
- Stellar activity records now extend over ~40 years:
- *Sun-like behavior observed for only 1 in 3 “cool stars”*



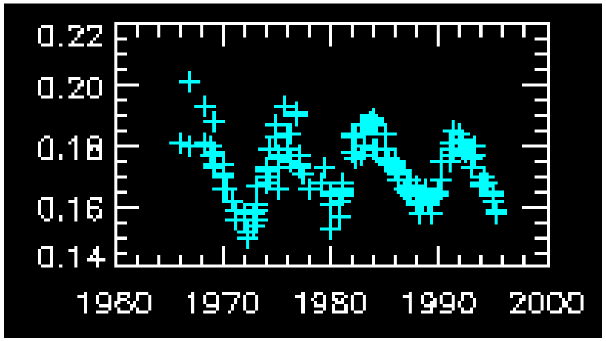
Sun ~2 billion years ago?

Less massive star

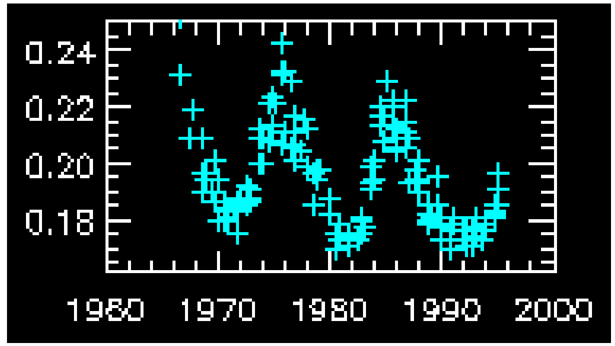
10^{10} year-old metal-deficient star; Sun ~5 billion years from now?

Flat Activity or Maunder minimum Sun?

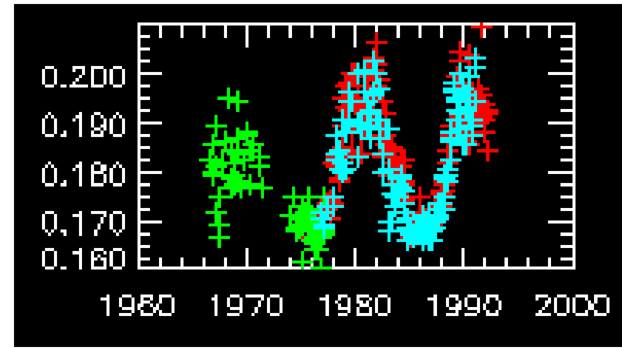
Temporal Patterns of Stellar Activity II.: Timescales



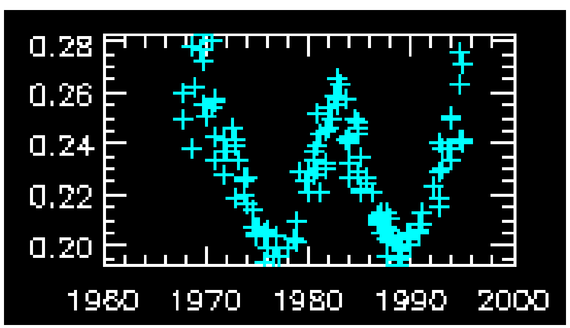
HD 81809: 8.2 yrs



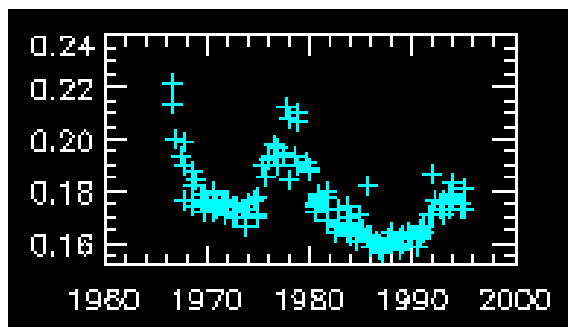
HD 10476: 9.6 yrs



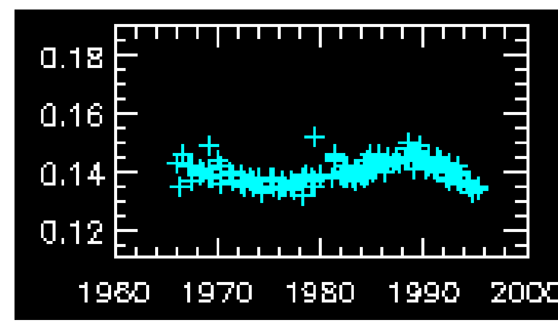
The Sun: 11 yrs



HD 16160: 13.2 yrs



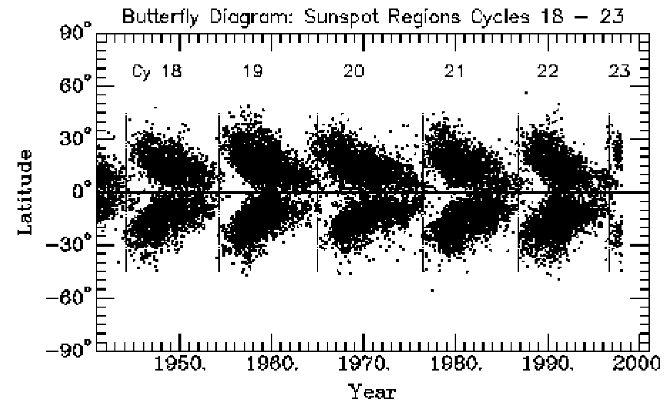
HD 3651: 13.8 yrs

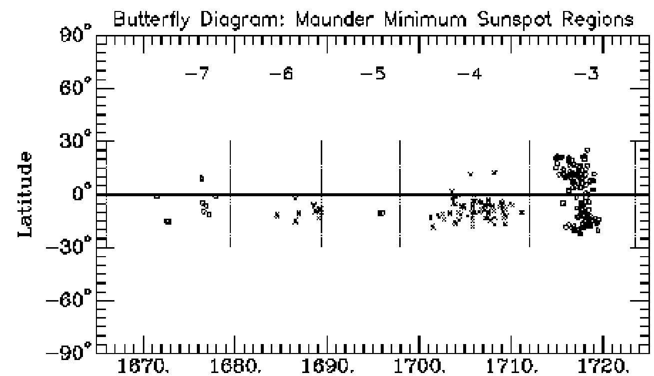


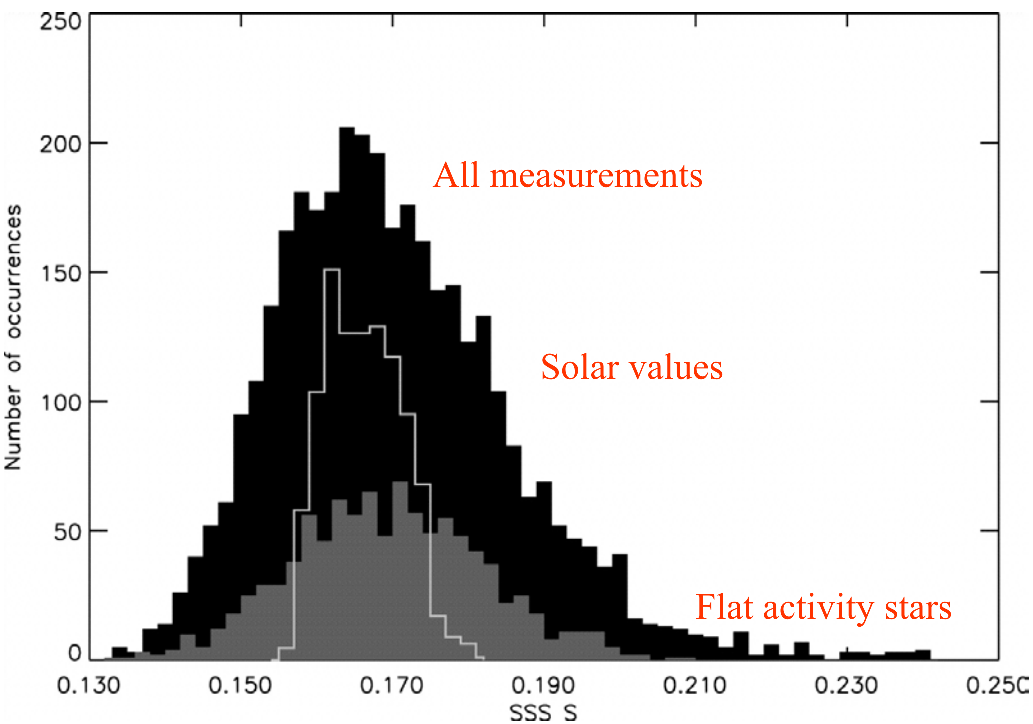
HD 136202: 23 yrs

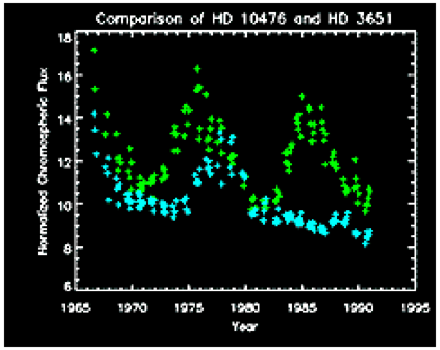
The Search for "Maunder Minimum" Stars

- What is a Maunder-minimum state?
  - Sunspots (hemispheric difference)
  - 11-year geomagnetic cycle
  - isotope modulation ~ cosmic-ray modulation
  - most of the aurorae originated in spot-free regions
    - in which some 40% of major flares occurred in recent times
- Do we know of any stars in a Maunder minimum state? ("flat activity" does not mean "no activity")



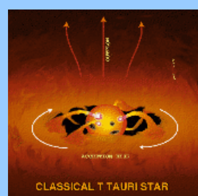






Solar-type dynamos/Astrophysical Magnetic Fields: Key Questions

- 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?

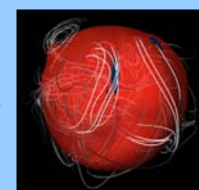


The cradle of life

? →

Stellar activity & planets, life

? →



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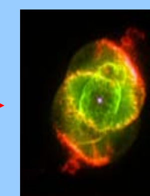


Dying giants

How does the dynamo evolve?

The Sun

Interacting binary

Accretion, jets, outflows

Accreting AGN

Can we generalize stellar dynamo properties?

The *Stellar Imager (SI)*

is a long-baseline, space-based, UV-optical observatory that will provide a (sub-mas) angular resolution more than *100x that of HST*.

It will resolve for the first time the surfaces of sun-like stars and the details of many other astrophysical objects & processes, e.g.:

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

Active Galactic Nuclei

transition zone between Broad and Narrow Line Regions;

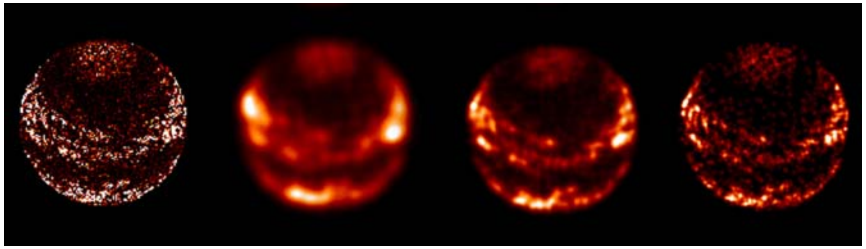
origin/orientation of jets;

distances

What Will Stellar Imager See?

Solar-type star at *4 pc* in *CIV line*

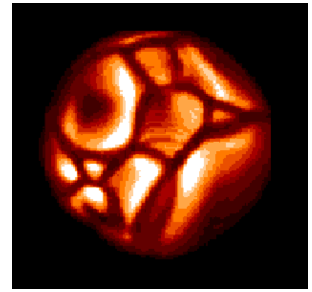
Model ***SIsim* images**



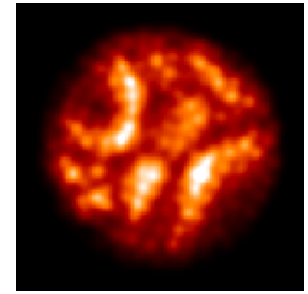
Baseline: 125m **250m** **500 m**

Evolved giant star at *2 Kpc* in *Mg H&K line*

Model

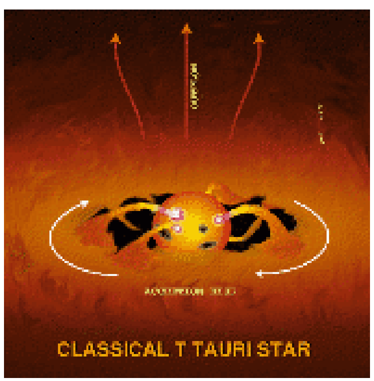


***SIsim* image (2mas dia)**

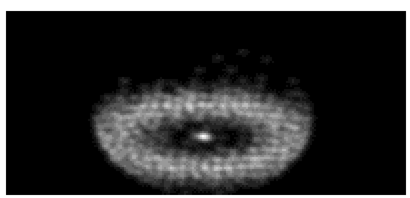


Baseline: 500 m

SI imaging of planet forming environments: magnetosphere-disk interaction region



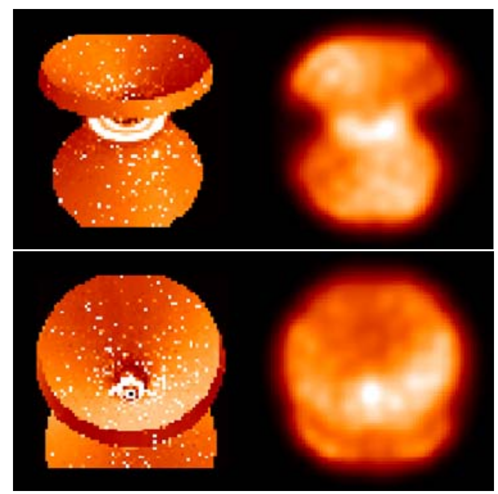
0.1 mas



***SI* simulation in Ly α–fluoresced H2 lines**

Baseline: 500 m

SI imaging of nearby AGN will differentiate between possible BELR geometries & inclinations



0.1 mas

model ***SI* simulations in *CIV line* (500 m baseline)**

SI and the NASA-ESA Strategies

– ***SI*** addresses the origins & evolution of structure & life in the Universe, and specific science goals of 3 research Themes in the NASA SMD
  - 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 Sun-Earth System (SSSC)

– ***SI*** complements the planetary imaging interferometers
  - ***Terrestrial Planet Finder-I (TPF-I)/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 and is a stepping stone towards crucial technology…
  - comparable in complexity to the ***Terrestrial Planet Finder-I***
  - will serve as technological & operational pathfinder for ***Life Finder (LF) and Planet Imager (PI)***

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

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.

SI Requirements Flow Down

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 @ 2000 Å

Spectral Range
- 1200 - 5000 Å

Field of View
- ~ 4 mas minimum

Flux Threshold at 1550 Å
- 5×10^{-14} 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

Required Capabilities for SI

- Wavelength coverage: 1200 – 5000 Å
- access to UV emission lines from Ly α 1216 Å to Mg II 2800 Å for stellar surface imaging
  - Important diagnostics of most abundant elements
  - much higher contrast between magnetic structures and background
  - smaller baselines (UV save 2-4x vs. optical, active regions 5x larger)
  - ~10-Å UV pass bands, e.g. C IV (100,000 K); Mg II h&k (10,000 K)
- broadband, near-UV or optical (3,000-10,000 K) for high time resolution spatially-resolved asteroseismology to resolve internal structure
- angular resolution of 50 micro-arcsec at 1200 Å (120 μas @2800 Å)
- ~1000 pixels of resolution over the surface of nearby dwarf stars
- enable energy resolution/spectroscopy of detected structures
- 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

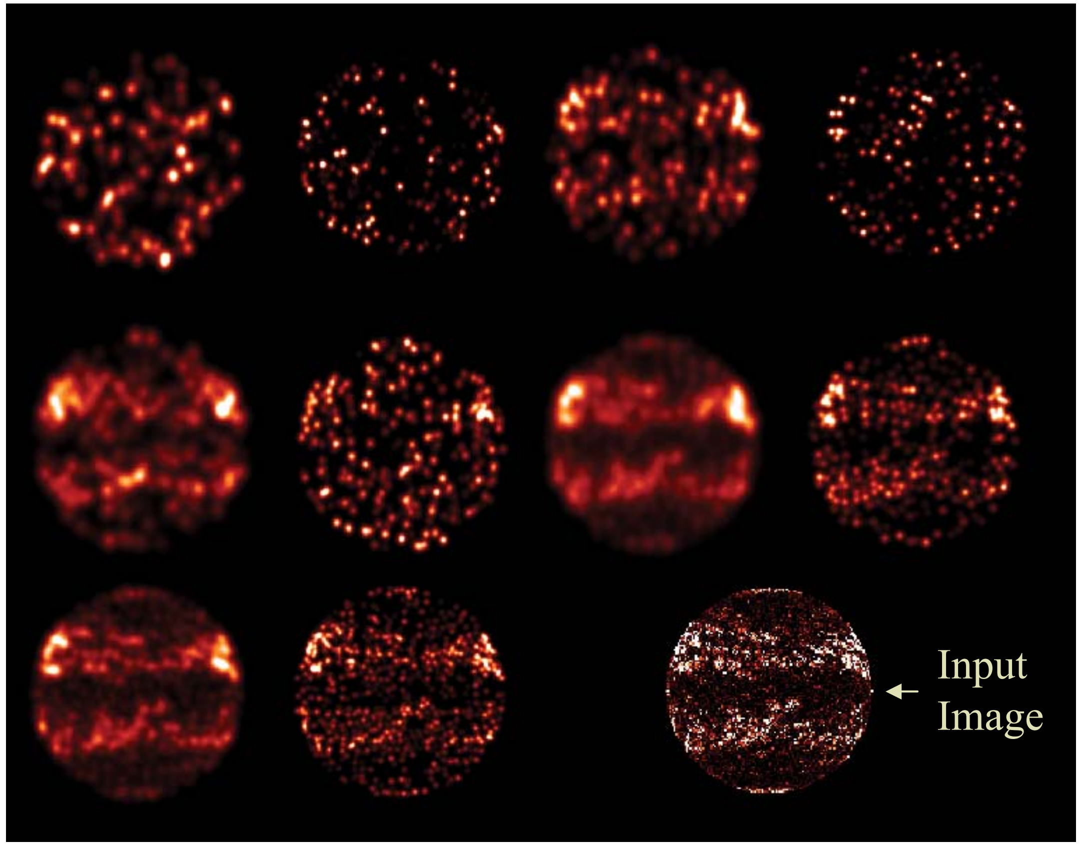
“Snapshots” (no rotations) (24 array rotations)

elements (layout)

6 (Y-array)

12 (Y-array)

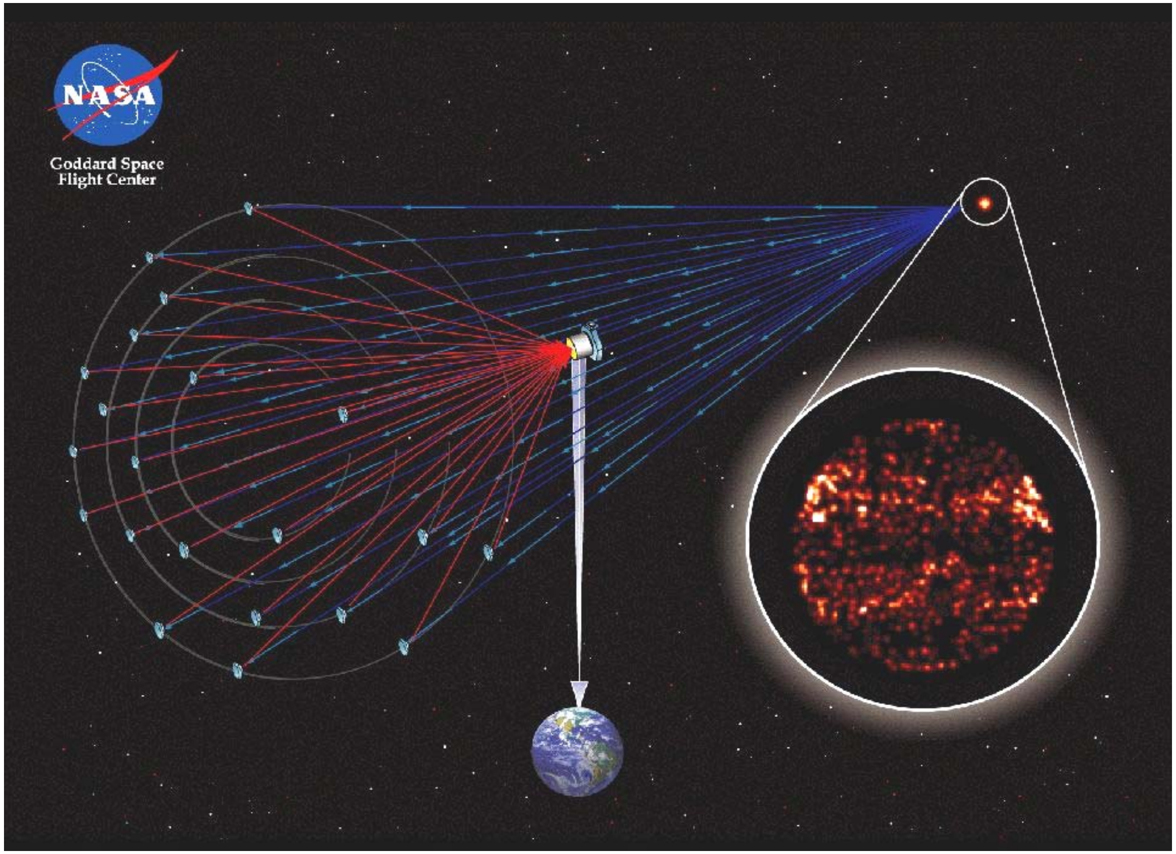
30 (Golomb Rectangle)



Baselines: 250 m 500 m 250 m 500 m

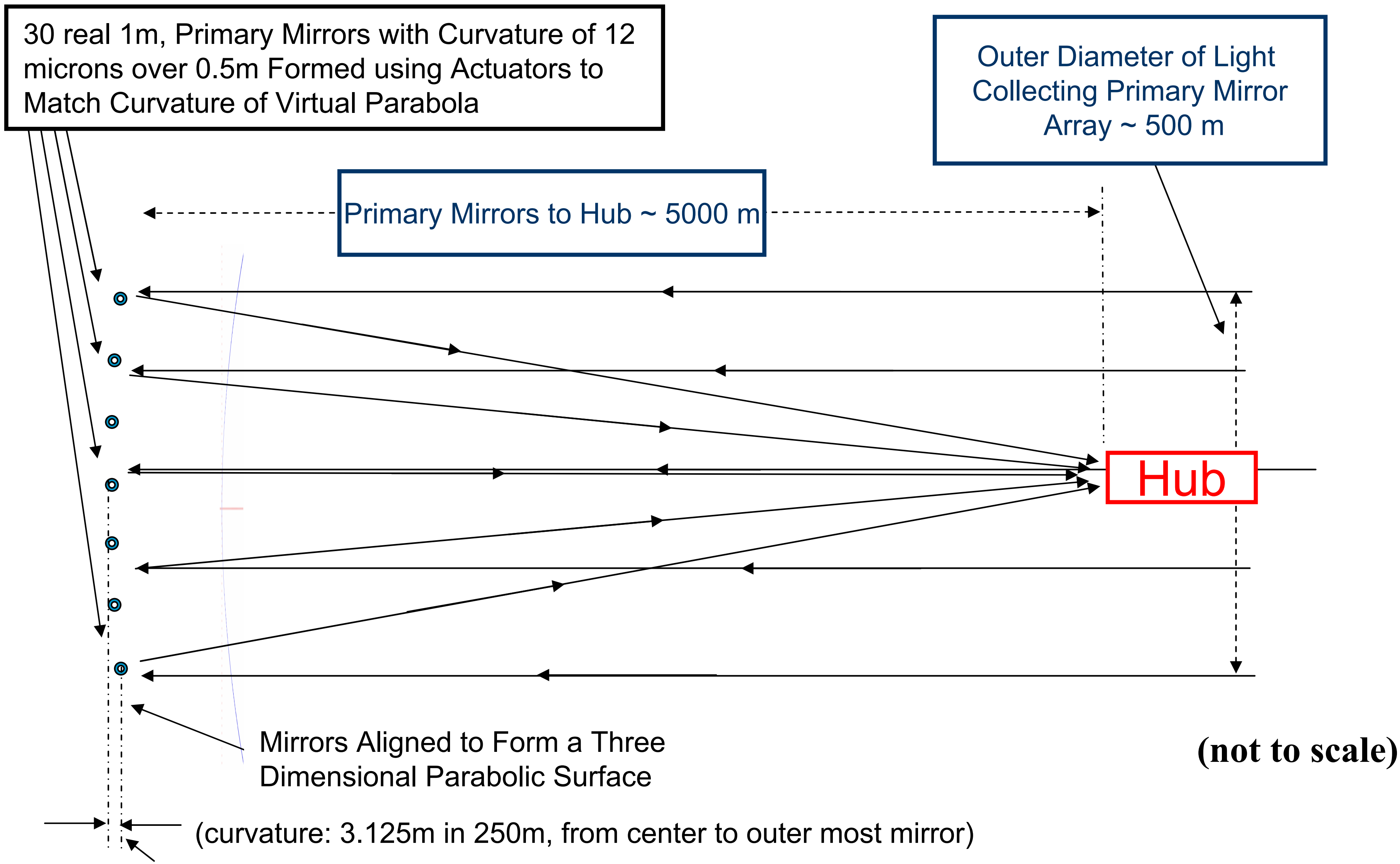
Simulations calculated using SISIM, written by R. Allen/J. Rajagopal, STScI

"Strawman" Concept



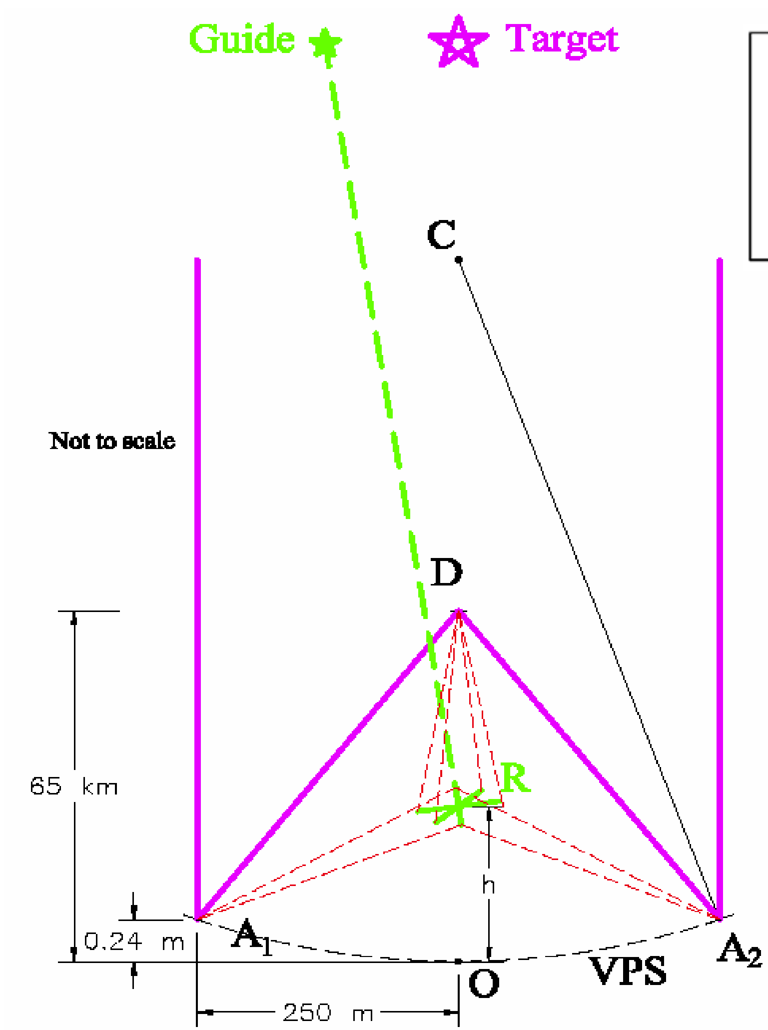
- a 0.5 km diameter space-based UV-optical Fizeau Interferometer
- located near Sun-earth L2 to enable precision formation flying
- 20-30 primary mirror elements focusing on beam-combining hub
- large advantages to flying more than 1 hub:
  - critical-path redundancy & major observing efficiency improvements

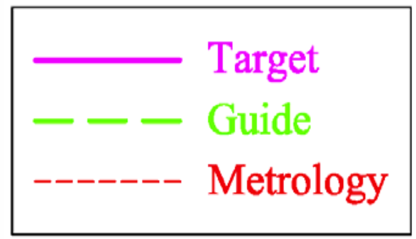
SI Cross-Sectional Schematic



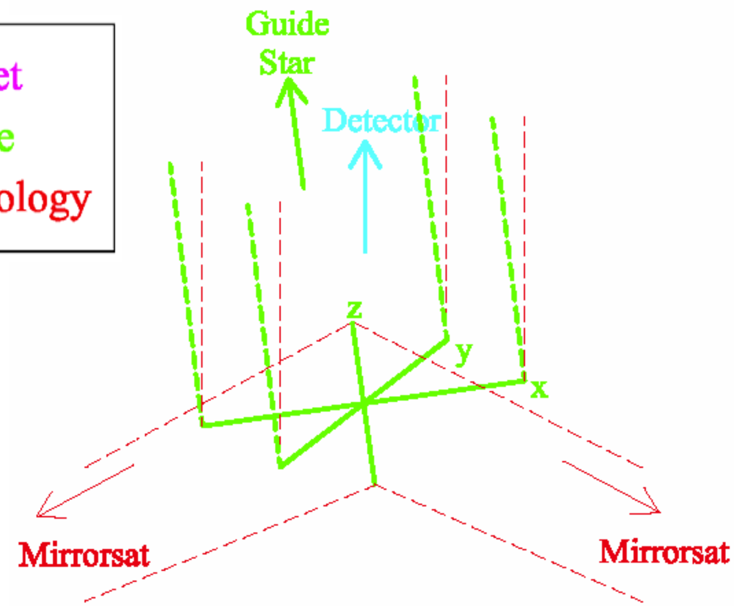
One Design for a Pointing Control System for SI

Stellar Imager





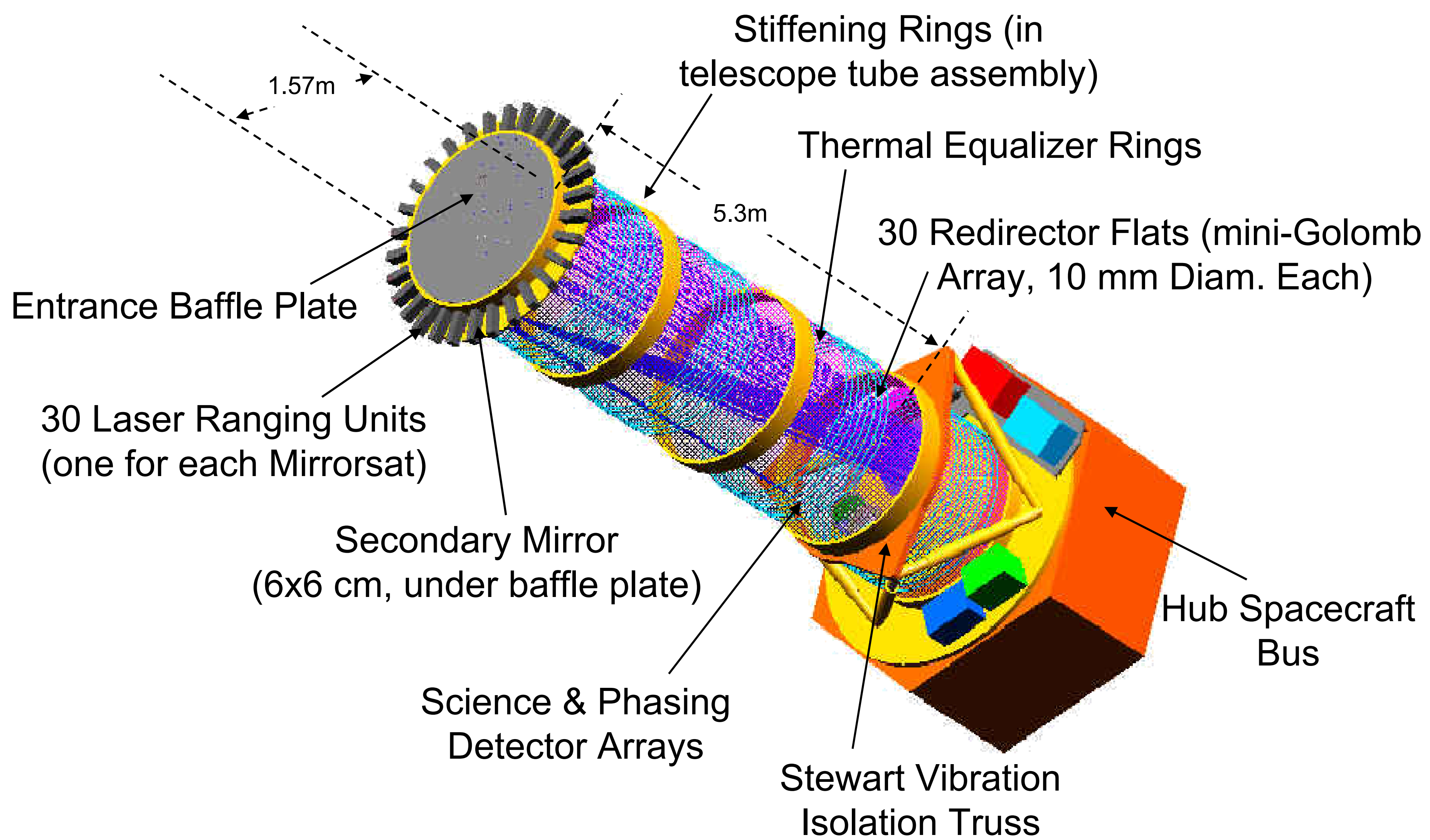
Reference Platform



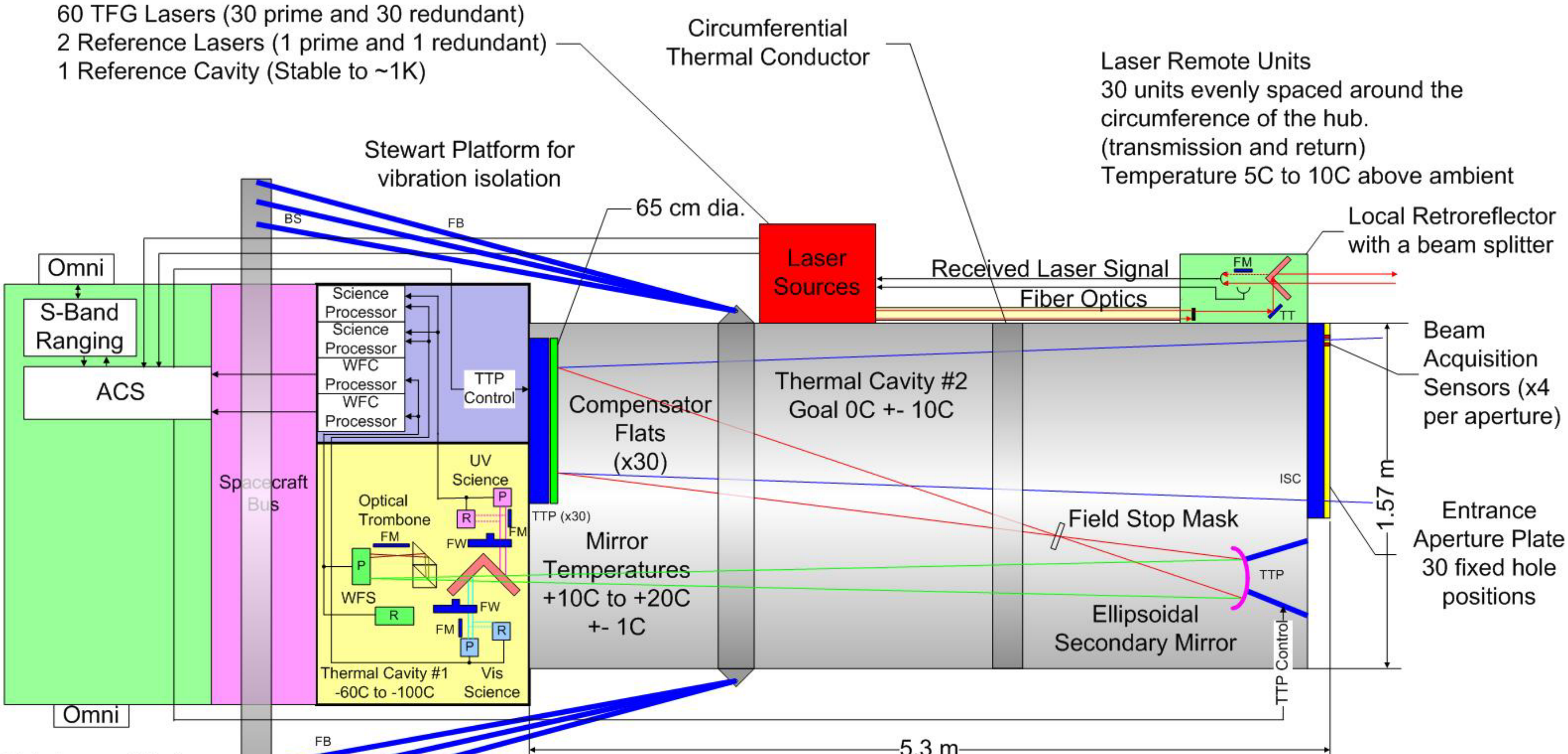
- Platform aligned with guide star within 1”.
  - Interferometers measure guide star offset to ~1 μas accuracy.

J. Phillips/SAO - October, 2004

Principal Elements of SI Hub



Hub Block Diagram



If Hub loses attitude control, make sure that you have enough omni antennas to prevent loss of RF ranging to Mirrorsats.

106 Mechanisms (shown in blue)

BSP	Bipod Strut Mechanism (x6)	FB	Frangi-Bolt Launch Lock Mechanism (x3)
FM	Flip Mirror Mechanism (x33)	FW	Filter Wheel Mechanism (x2)
ISC	Internal Shutter/Cover Mechanism (x1)	TT	Tip/Tilt Mechanism (x30)
TTP	Tip/Tilt/Piston Mechanism (x31)		

PROPULSION

- Current Choices

  – Hydrazine propulsion systems on the Mirrorsat Dispenser and the Hub correct for launch vehicle errors & insertion into L2 orbit.

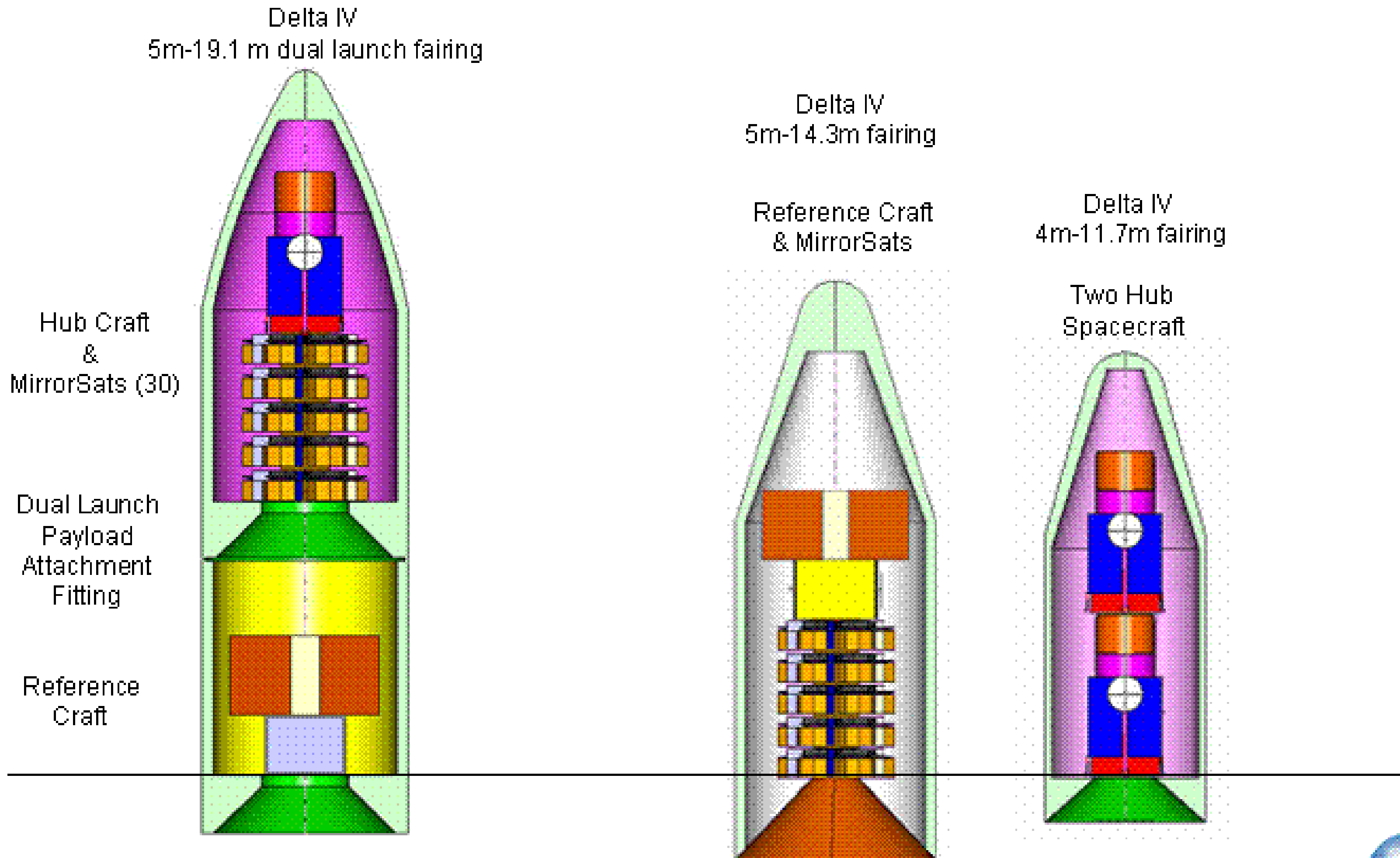
  – Hydrazine propulsion systems are discarded after insertion of the Mirrorsat + Dispenser & the Hub into the L2 orbit

  – Science manuevers for 10 years, including L2 orbit maintenance & constellation station keeping, are performed with μN thrusters, such as Indium Field Emission Electric Propulsion (FEEP).

  – Hub S/C slews accomplished with Hall thrusters

Launch Configuration
Dual vs. Single Launch

Integrated Mission Design Center



4-7 Oct 2004
SI-VM

Sensitive Information
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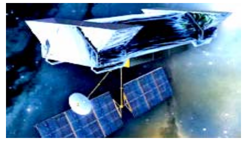
Mechanical, p3
Final Version

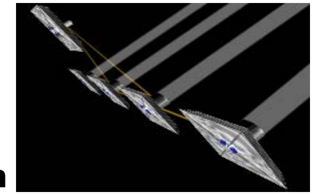
Top Technological Challenges and Enabling Technologies

- **formation-flying of ~ 30 spacecraft**
  - deployment and initial positioning of elements in large formations
  - real-time correction and control of formation elements
    - staged-control system (km → cm → nm)
  - aspect control to 10's of micro-arcsec
  - positioning mirror surfaces to 2 nm
  - variable, non-condensing, continuous micro-Newton thrusters
- **precision metrology** (2 nm over multi-km baselines)
  - multiple modes to cover wide dynamic range
- **wavefront sensing and real-time, autonomous analysis**
- **methodologies for grd.-based validation of distributed systems**
- **additional challenges**
  - mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test
  - long mission lifetime requirement
  - light-weight UV quality mirrors with km-long radii of curvature (perhaps using deformable UV quality flats)
  - larger format (6 K x 6 K) energy resolving detectors with finer energy resolution (R=100)

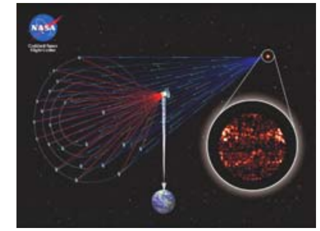
Development of Space Interferometry



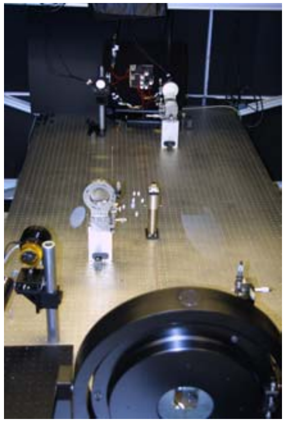
SIM
- Precision Metrology
- Boom Interferometer
- TPF Targeting



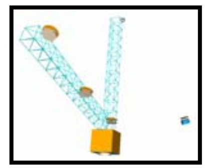
TPF-I/Darwin
- Planet Detection, Spectroscopy
- Free-flying IR Nulling Interferom.
- 0.75 mas; PI & LF Targeting



Stellar Imager
- Stellar dynamos
- UV/Optical Interferom.
- < 0.1 mas resolution

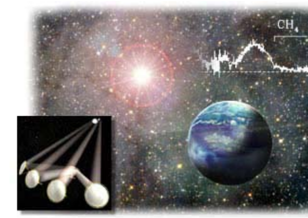


ST-9 or Smart-3
- Precision Formation Flying
- Possible Interferometry

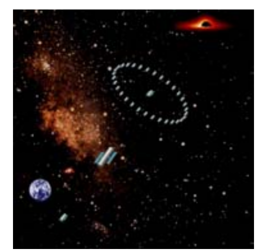


SI Pathfinder
- UV/Optical Interferometry
- Formation Flying

Grd-Based Testbeds
- Wavefront Sensing/Control:
  - FIT, STAR9
- Formation Flying:
  - SIFFT, FFTB, FCT



Life Finder
- Searching for Signs of Life



Black Hole Imager
- X-ray Interferom.

Planet Imager
- Terrestrial-Planet Imaging

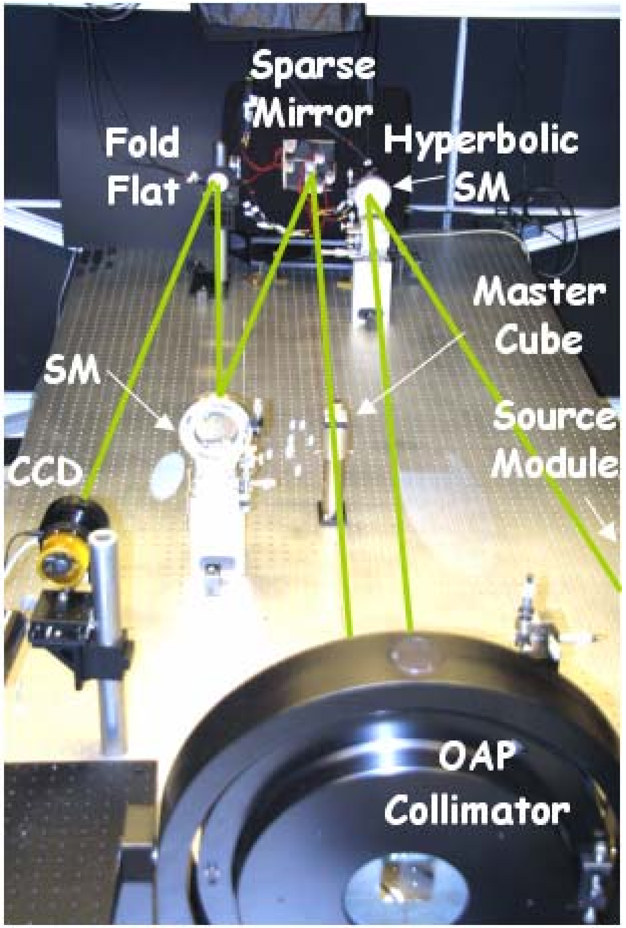
Ground-based interferometry (Keck,VLTI,LBT)
- Giant star imaging
- Binary stars

2005 — 2010 — 2015 — 2020 — 2025 +

The GSFC Fizeau Interferometer Testbed (FIT):
Developing Closed-Loop Optical Control for Large Arrays

K. Carpenter, R. Lyon, K. Hartman/GSFC; P. Petrone, P. Dagoda, J. Marzouk/Sigma Space, D. Mozurkewich/Seabrook Eng., T. Armstrong & X. Zhang/NRL, L. Mundy/UMD

- **A ground-based testbed which will**
  - explore principles of and requirements for Stellar Imager & other Fizeau Interferometer/Sparse Aperture Telescope missions (e.g. MAXIM, LF, PI), to enable their development and reduce technical and cost risks
  - utilize 7-20 separate articulated apertures, with tip, tilt, and piston automatically controlled on each
  - validate new and existing analytic and computational models to ensure realistic performance assessment of future flight designs
  - demonstrate closed-loop control of system based on analysis of science data stream
  - evaluate and demonstrate performance of new and existing image synthesis algorithms and successful image reconstruction from actual laboratory sparse aperture/interferometric data



The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT):
Proposed in Response to 2005 NASA APRA ROSES NRA

*K. Carpenter, R. Lyon, K. Hartmann/GSFC; P. Stahl/MSFC, D. Miller/MIT,
J. Marzouk/Sigma Space, D. Mozurkewich/Seabrook Eng.*

- **A ground-based testbed which will**
  - In combination with FIT enable synergistic develeopment of technologies needed to support space-borne synthetic aperture ultra-high resolution imaging
  - Develop and demonstrate algorithms for autonomous precision formation flying which can, in the future, be combined with higher precision optical control systems
  - Set requirements for future staged-control systems
  - Be created at relatively low cost by utilizing equipment from existing MIT-developed SPHERES (**S**ynchronized **P**osition **H**old **E**ngage and **R**eorient **E**xperimental **S**atellites) experiment on the MSFC Flat Floor Facility
  - Areas of investigation include:
    - Formation Capture (deployment)
    - Formation Maintenance
    - Formation Reconfiguration
    - Synthetic Imaging maneuvers (retargeting and reconfig.)

One SPHERES unit

Five SPHERES on air carriages on MSFC Flat Floor

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

Tentative Schedule

2005: Complete Vision Mission Study

2005-08: Continue studies of multi-element fine optical control with Fizeau Interferometer Testbed (FIT)

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, detectors

2006: Develop Pathfinder Concept suitable for future “Origins/Universe Probe” type opportunities

2007: Propose Pathfinder Mission

~2015: Fly pathfinder mission

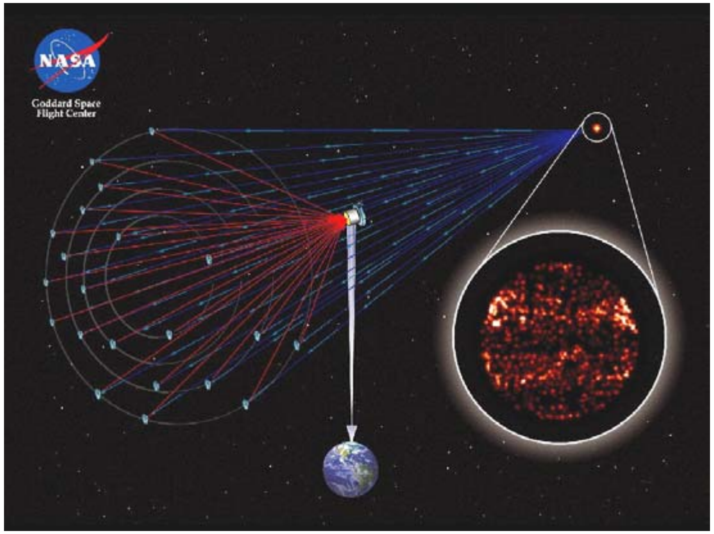
~2025: Fly full mission

SI Status

- SI in NASA SEC (now SSSC) Roadmap since 2000
- SI selected for further concept development by the NASA HQ 2003 Vision Mission NRA review
- Major Partnerships established with LMATC, SAO, BATC, NGST, JPL, 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) and Instrument Synthesis and Analysis Lab (ISAL) studies executed (10/2004; 2/2005) to produce a system design & technology development roadmap
- SI presented to SEU/Origins, SSSC, APIO, Universe Roadmap Committees (Nov. 2005 →)
- **In the May, 2005 NASA Strategic Roadmaps, SI is included as**
  - **A "Flagship" (Vision) mission in the SSSC Roadmap**
  - **A candidate "Pathways to Life Observatory" in the EUD Roadmap**

Summary: Stellar Imager (SI) Vision Mission

- UV-Optical Interferometer to provide 0.1 mas imaging (+ spectroscopy) of
  - magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, transport processes on many scales in 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)

improve long-term forecasting of solar and stellar magnetic activity

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

understand transport processes controlled by magnetic fields throughout the Universe

perform high angular resolution studies (imaging + spectroscopy) of Active Galactic Nuclei, Quasars, Supernovae, Interacting Binary Stars, Forming Stars/Disks

Appendix: Supplemental Information

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

Electric Propulsion

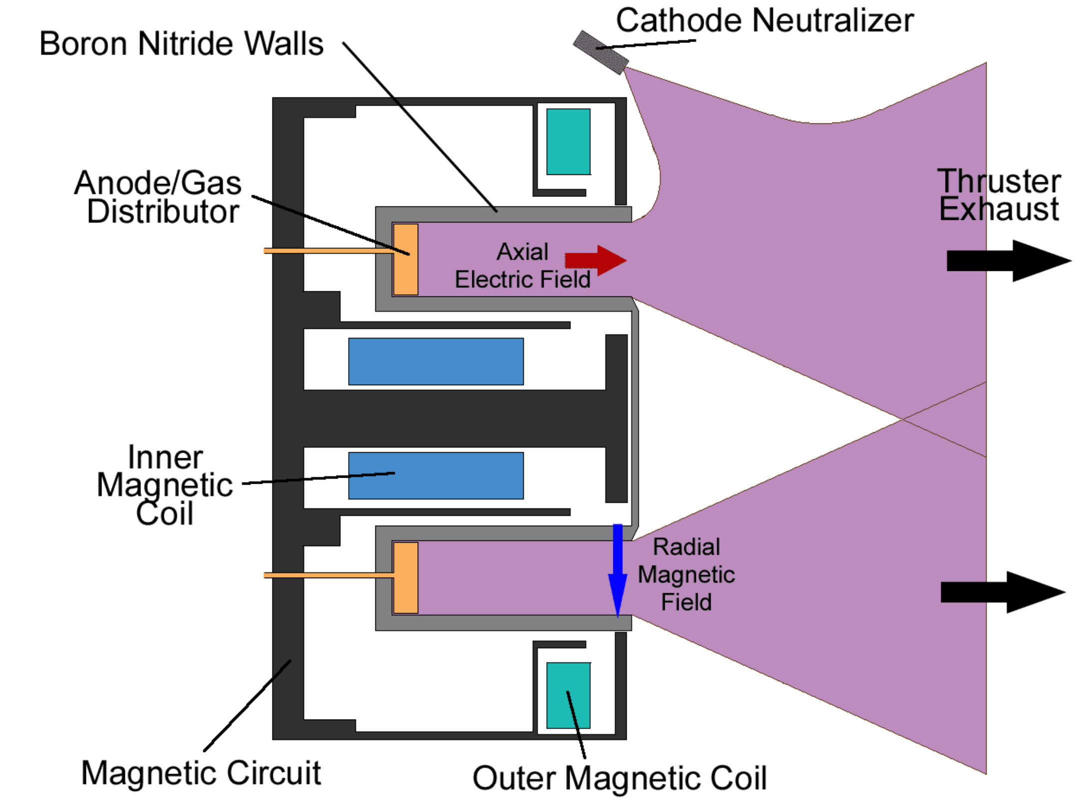
- Significant differences between electric propulsion and classical chemical
- No energy extracted from fuel (no chemical reactions) – all energy for thrust from solar array or other electrical source
- Low thrust
- High efficiency
- High power requirements, low fuel storage volume requirements
- Great for accumulating large del-V over long periods of time
- Poor for high accelerations
- Low thrust is great for fine pointing
- Thrust level can be throttled
- The weight of a quarter is approximately 60 mN

Low Thrust Electric Propulsion Technologies

	Cold Gas	Colloidal	FEEP (Field Effect Electric Propulsion)	μ Chemical	μ Ion
Propellant	N_2, He	EMI-Im	Cs, In	N_2H_4 / H_2O_2	Xe, Ar
Isp (s)	80, 180	1000	5000	200 / 150	2500-1500
Effluent	N_2, He	Droplets	Ions	N_2, H_2, NH_3 / H_2O, O_2	Xe^+, Ar^+
Plume Type	Gas Plume	10º cone	10º cone	Gas Plume	Wide Plume
Effluent Condensation Temp (K)	77, 4	260	302, 430	77, 14, 195 / 373, 90	165, 84
Thrust Range (μN)	100+	5-30	0.1-100	50-500	50-500
TRL	8	6	4	2	3

Hall Effect Thrusters

- Description: Hall thrusters
  - Axial electric field accelerates ions. Combining radial magnetic field generates an azimuthal Hall current. Current interacts with the radial magnetic field producing a volumetric (j X B) accelerating force on the plasma
  - Developed by the former Soviet Union
  - Uses Xenon gas: high molecular weight, low ionization potential
- Current research on Hall thrusters is ongoing and focuses mainly on:
  - Scaling the typically 1kW Hall thrusters to higher and lower powers
  - Resolving spacecraft integration and contamination issues
  - Enabling operation at higher Specific impulse and variable specific impulse
- Current Perf. (conservative)
  - Thruster efficiency: 50-65%
  - Specific impulse: 1800-3000 seconds
  - Thrust to power ratio: 40 - 70 mN/kW



Interesting Hall Thruster Info from the Web

- For comparison, the weight of a quarter is approximately 60 mN.
- Over 100 Hall thrusters have been flown on Soviet/Russian satellites in the past thirty years. They were used mainly for stationkeep and small orbital corrections.
- The T-220 was developed by the NASA Glenn Research Center (GRC), TRW, and Space Power Incorporated under the NASA Advanced Space Transportation Program.
  - The thruster provides over 500 mN of thrust at a specific impulse of 2450 sec and 59-percent total efficiency with 10 kW of input power
  - Operate at 7 to 20 kW and produce 0.5 to 1.0 N of thrust with specific impulse values varying between 1,500 and 2,500 seconds
  - T-220HT Exceeds 0.6 N/kW and thrust-per-unit power of 0.65–0.70 N/kW
- T-140 Hall Effect Thruster is an ideal size for north-south station keeping for large satellites. The T-140 operates at 1.8 to 4.5 kW and produces 160 to 300 mN of thrust, with specific impulse values varying between 1,800 and 2,200 seconds
- NASA-Glenn successfully designed, built, and tested a laboratory Hall thruster capable of producing more than 3 N of thrust, a record for a Hall device. The thruster's power ranged from 9 to 72 kW and the specific impulse from 2,000 to 3,000 sec.
- The NASA Evolutionary Xenon Thruster (NEXT) is designed to deliver a throttleable 7- kW, 40-cm ion thruster with a xenon throughput capability of over 400 kg, a specific impulse (Isp) of 2,200-4,120 sec, and a thrust of 50-210 mN
- NASA-Glenn and Aerojet: Selected to begin the Hi-Voltage Hall Accelerator program to develop a Hall thruster targeting the 6-8-kW, 2,200-2,800-sec Isp performance range.

L2 Orbit Propulsion System

- **Mirrorsats**
  - Precision Attitude & Translation Control Thrusters: 12 x 10-50 μN Indium FEEP
  - Translation Thrusters: 4 x 100 μN Indium FEEP
  - Assumed FEEP Performance
    - Isp = 5000 sec
    - total = 60 W during firing (70 W from array), 50% power efficiency
- **Hub S/C**
  - Precision Attitude & Translation Control Thrusters: 12 x 10-50 μN Indium FEEP
  - Translation Thrusters: 4 x 100 mN Hall thrusters
  - Assumed Hall Performance
    - Isp = 1800 sec (conservative), 65 mN/kW (lab scale SOA)
    - total = 1500 W during firing , 85% power efficiency (1800 W from array)