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Imaging the Surfaces and Interiors of Other Stars: The *Stellar Imager (SI)* Mission Concept

Kenneth G. Carpenter and Richard G. Lyon[1], Carolus J. Schrijver[2], Lee J. Mundy[3], Ronald J. Allen and Jay Rajagopal[4]

Abstract.
The *Stellar Imager* (*SI*) is envisioned as a large (0.5 km diameter) space-based, UV-optical interferometer. It is designed to image surface features and, through asteroseismology, sub-surface structures of other stars and measure their spatial and temporal variations. These observations are needed to improve our understanding of the underlying dynamo process(es) and enable improved forecasting of solar/stellar activity and its impact on planetary climates and life. Schrijver and Carpenter (this volume) discuss the science goals of the mission in detail, while in this paper we discuss the performance requirements implied by the science goals and how these translate into specific design requirements on the mission architecture, and we present some preliminary visions for how the required observations (e.g., 1000 pixel, *100 micro-arcsec* resolution, UV-optical images of the surface of nearby dwarf stars) for this ambitious project might be obtained.

1. Science, Performance and Design Requirements

There are **two broad science requirements for the mission, both of which require a population study of cool stars representing a broad range of magnetic activity**: imaging to detect and monitor the evolution of active regions and asteroseismology (acoustic imaging) to obtain information on the sub-surface layers. To understand the dynamo, we need to know how magnetic fields are generated and behave in different circumstances - the sun is only one example and provides insufficient constraints on theories of dynamos, turbulence, structure, and internal mixing. *We must observe other stars to establish how mass, rotation, brightness and age affect the patterns of activity* and determine: What determines cycle strength and duration? Can multiple cycles exist at the surface? How do polar spots form? How common is solar-like activity? What are extremely (in)active stars like? What are Maunder-minimum states like? Although its clearest manifestations are visible on the stellar surface, *a*

[1]NASA's Goddard Space Flight Center

[2]Lockheed-Martin Advanced Technologies Center

[3]University of Maryland

[4]Space Telescope Science Institute

full understanding of the dynamo requires a knowledge of the underlying layers: Where is the seat of the dynamo? What determines differential rotation and meridional circulation, and what role do they play in the dynamo? What is the impact of magnetic deceleration on internal rotation and stellar evolution? How are stellar interiors modified in extremely active stars?

The following **primary performance goals** have been established to address the science goals outlined above: 1) image a substantial sample of nearby dwarf and giant stars representing a broad range in magnetic activity, obtaining a resolution of order 1000 total pixels (33x33), equivalent to ∼50,000 km resolution on a Sun-like star at 4 pc., 2) study a sample in detail, revisiting over many years, and measure sizes, lifetimes, and emergence patterns of stellar active regions, surface differential rotation, field dispersal by convective motions and meridional circulation, and directly image the entire convection spectrum on giant stars and the supergranulation on, e.g., the solar counterpart Alpha Centauri and 3) enable asteroseismology, using low to intermediate degree non-radial modes to measure internal stellar structure and rotation.

The **design requirements for imaging of stellar surface activity** include the acquisition of UV images to ensure visibility of surface manifestations of the dynamo. Dark starspots in the visible-light photosphere are small in most stars and have low contrast with the surrounding bright stellar surface. High-contrast bright spots are seen in UV (chromospheric, transition-layer) emission (e.g., Mg II h&k 2800 Å, C IV 1550 Å) from plages above surface wherever it is penetrated by strong magnetic fields, making them the ideal activity diagnostics. Modest integration times (∼hours for dwarfs to days for giants) are required to avoid smearing of images due to rotation, proper motions, and activity evolution.

Design requirements for imaging of stellar interiors by seismology include short integration times (minutes for dwarf stars to hours for giant stars) and thus broadband optical wavelengths to get sufficiently high fluxes, low-resolution imaging to measure non-radial resonant waves (∼30-100 total resolution elements over the stellar surface). Flexible interferometer configurations are required for both surface and sub-surface image synthesis.

2. Strawman Mission Concept

The current leading architecture concept for *Stellar Imager (SI)* is that of a 0.5 km diameter, space-based, UV-optical Fizeau Interferometer composed of a reconfigurable array of 10 - 30 one-meter-class (spherical or flat) array elements on small satellites ("mirrorsats"). Those elements direct light to an image-plane beam combination facility in a hub at the prime focus, as shown in Fig. 1. A variant of the "pupil densification" approach (Labeyrie, 1996) is under consideration as well, though not shown here.

This design would provide: an angular resolution of 60 and 120 micro-arcsec at 1550 Å and 2800 Å, ∼1000 pixels of resolution over the surface of nearby dwarf stars, observations in ∼10-Å UV pass-bands around, e.g., C IV (100,000 K) and Mg II h&k (10,000 K), and broadband observations in the near-UV or optical continuum (formed at 3,000-10,000 K). It is designed as a long-term mission with a requirement of a 10 year lifetime and a goal of 20 years, to allow the study

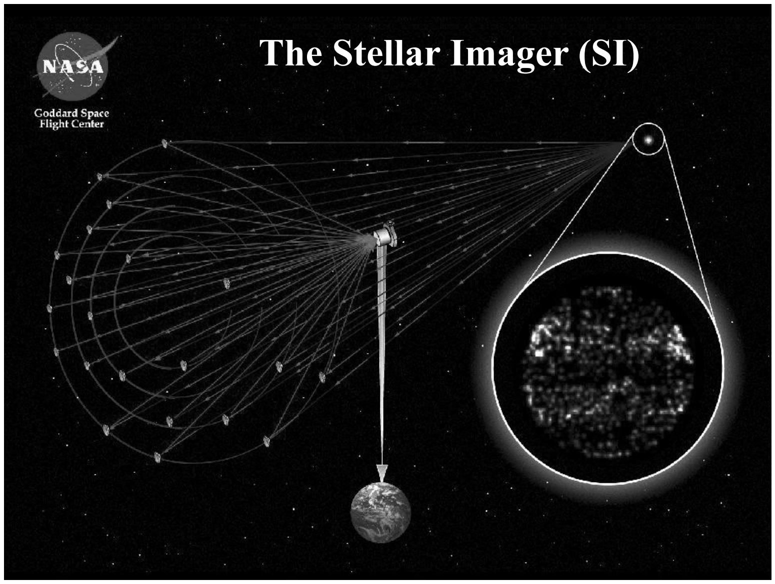

Figure 1. An artist's concept of a 30-element Fizeau Interferometer design option for *SI*.

of significant portions of stellar magnetic activity cycles. Individual telescopes and the central hub can be refurbished or replaced as needed.

SI will be located in a Lissajous orbit around the sun-earth L2 point. It cannot be in low-earth orbit because the strong gravity gradient there would not permit precise formation flying (and there is a potential scattered light problem as well). An earth-trailing orbit is not desirable since replacement of failed array elements and addition of improved (larger) array elements would not be possible. L2 has both a small and very well characterized gravity gradient to permit precise formation flying and should be accessible in the 2015 time frame for servicing and upgrade by robotic and/or manned missions.

A Fizeau is preferred over a Michelson design because it tremendously simplifies the beam-combination station and thus substantially lowers the cost of using many array elements. The use of many array elements enables quick acquisition of data to support imaging of transient stellar surface features (intrinsic variations, plus rotational and proper-motion-induced blurring) and high-time resolution asteroseismology, and it minimizes number of re-configurations of the array needed to obtain the required number of baselines to ensure the desired image quality (# baselines $\approx$# pixels). Other benefits are that low consumption of propellant enables desired long-duration mission, overhead time for reconfigurations is minimized, observing efficiency and ability to image time-dependent phenomena are maximized, and the number of reflections in the system is minimized, which is critical to maintain UV sensitivity.

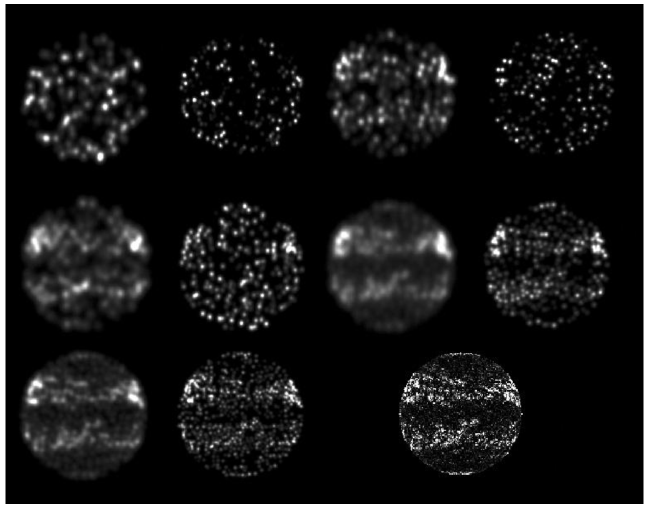

Figure 2. Simulated interferometric (CIV (1550 Å)) images of a sun-like star at 4 pc, viewed equator-on, based on the model solar image at bottom right. See text for details.

2.1. Simulated Stellar Images

The images that could be obtained with the strawman mission design are illustrated in Fig. 2 for various numbers of elements and re-configuration strategies. These simulations were computed with SISIM (developed by R.A. and J.R.) assuming 250 (first and third columns) and 500 (second and fourth columns) meter maximum baseline arrays. The first two rows assume Y-shaped configurations with 6 and 12 elements, respectively. The last two columns of those rows assume that the array is rotated 24 times (15 degree motions) to acquire sufficient Fourier UV-plane sampling. The 1st two images in the last row assume 30 elements arranged in a low-redundancy Golomb rectangle (Golomb & Taylor, 1982). The first two columns in all cases show snapshots taken without rotating the arrays.

This figure shows that 30 static elements appear to be sufficient to adequately synthesize this particular stellar image. The 435 baselines provided by the static 30-element array works well because only about half of the 1000 pixels in the image are truly filled. If all the image pixels were filled (or a large number of the remaining pixels), then a second configuration of the array (e.g., a 90 degree rotation) would be necessary for sufficient sampling. Alternatively, fewer elements can be used with a larger number of rotations (6 elements with 24 rotations or 12 elements with 6 rotations).

2.2. Results of Initial GSFC Integrated Mission Design Center Study

The baseline concept studied by the IMDC was for a spaced-based Fizeau interferometer, located in a Lissajous orbit around the sun-earth L2 point, with a 0.5 km maximum baseline and 4 km focal length. The design considered included 30 mirrorsats formation flying with a beam-combining hub, where the satellites are controlled to 5 nm precision, rather than using optical delay lines inside the hub for fine tuning the optical path lengths. A variety of disciplines considered the implications of this general design, including power, guidance & navigation, flight dynamics, operations, communications, quality assurance, system engineering, etc. The highlights of this very preliminary study are summarized here.

Launch requirements are not prohibitive - 3 good options exist: 3 Delta III, 1 Atlas V, or 2 Delta (III/IV) launches. The preferred option is a dual launch of Delta IV 4450-14 (mirrorsats & dispenser) + Delta III 3940-11 (hub), which allows for 30 134-kg mirrorsats + one 2600 kg hub. Power requirements can be handled by existing solar cells, but must be body-mounted to avoid unacceptable impact on precision formation-flying and station-keeping. Battery life and storage are a concern. Propellant requirements at L2 are modest: Field Emission Electric Propulsion (FEEP) should be capable in the 2015 timeframe of generating continuous, variable μ-Newton thrust for required 10 year lifetime on less than 0.2 kg (mirrorsats) or 1 kg (hub) of solid fuel. The operations concept is straightforward and assumes autonomous control of array station-keeping, reconfiguration, and slewing, with ground interaction only for command uploads and anomaly resolution. The main concern of the thermal engineers is keeping mirrors isothermal.

Communications requirements are not excessive. In normal operations the mirrorsats talk to the hub and each other, and the hub talks to earth. In contingency operations: mirrorsats can be commanded directly from earth. A desired enhancement in this area would be a central communications hub at L2 for all missions flying in that locale.

Precision metrology and formation-flying are the tallest poles among numerous technical challenges. A 3-level approach envisioned rough formation control via radio frequency (RF) ranging and thrusters (to m's), intermediate control (to cm's) via modulated laser ranging, and fine control (to nm's) via feedback from science data system/phase diversity analysis. The long mission lifetime requirement was the second biggest concern among the designers: the hub will have redundant components, but we need to seriously consider building backup hub for launch-on-need or original deployment and we would need to fly additional backup mirrorsats to put into the operating array as the original set suffers expected failures (the mirrorsats were designed as inexpensive, low-redundancy, mass-produced craft in this study).

The most important enabling technologies identified in the IMDC study as needing further study and development include: deployment/initial positioning of elements in large formations, metrology/autonomous nm-level control of many-element formations over kilometer scales, aspect control to 10s of μarcsecs, variable, non-condensing continuous μ-Newton thrusters, light-weight UV quality spherical mirrors with km-long radii of curvature, and larger format energy resolving detectors with finer energy resolution (R=100).

3. Ground-Based Testbeds

Two ground-based laboratory testbeds at GSFC for UV-Optical Fizeau Interferometers/Sparse Aperture Telescopes are being developed: the Phase Diverse Testbed (PDT) and the Fizeau Interferometry Testbed (FIT). The PDT is nearing completion now and utilizes a masked filled-aperture to simulate a system with 3 moving apertures. It enables testing of Phase Diversity algorithms which will allow the determination of optical wavefront needed to drive control systems to maintain adequate phasing for high-resolution imaging from an array of formation-flying spacecraft. The FIT is in the design and development stage now. It is designed to explore the principles of and requirements for the *Stellar Imager* mission concept and other Fizeau Interferometers/Sparse Aperture Telescope missions. It utilizes a large number of truly separate, articulated apertures (each with 5 degrees of freedom: tip, tilt, piston, 2D translation of array elements) in a sparse distribution. It has the long-term goal of demonstrating closed-loop control of articulated mirrors and the overall system to keep beams in phase and optimize imaging. It enables critical assessment of various image reconstruction algorithms (phase diversity, clean, MEM, etc.) for utility and accuracy by application to real data.

4. Summary/Status

SI is currently included in the far-horizon NASA Sun-Earth Connection Roadmap. The mission concept continues to be developed by NASA/GSFC in collaboration with LMATC, NRL/NPOI, STScI, UMD, etc. Further information on the mission can be found on the web at URL's: http://hires.gsfc.nasa.gov/∼si and http://www.lmsal.com/SISP, where a draft white paper, various science and concept presentations, and images are available for download. A summary paper which includes discussion of the context for *Stellar Imager* and its possible use for other scientific objectives can be found in Carpenter et al. (2001). Requirements have been defined for a Laboratory Fizeau Interferometry Testbed (FIT) at GSFC and an preliminary GSFC Integrated Mission Design Center (IMDC) study has been performed. We continue with architecture and trade/feasibility studies and plan to test and demonstrate design concepts with the ground-based testbed. Finally, we plan to gather and utilize additional community input and produce a book summarizing the science and societal motivations for the mission, the technology roadmap, and the most promising architecture options. *We invite you to join us in the definition and realization of this mission.* Please contact K. Carpenter (kgc@stargate.gsfc.nasa.gov) or C. Schrijver (schryver@lmsal.com) with your comments and suggestions.

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