The Stellar Imager (SI): An Ultra-High Angular Resolution Ultraviolet/Optical Observatory

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Abstract. The Stellar Imager (SI) is envisioned as a space-based, ultraviolet-optical interferometer composed of 10 or more one-meter class elements distributed with a maximum baseline of 0.5 km and providing a resolution of 60 micro-arcseconds at 1550 Å. It will image stars and binaries with sufficient resolution to enable long-term studies of stellar magnetic activity patterns and their evolution with time, for comparison with those on the Sun. It will also sound their interiors through astroseismology to image internal structure, differential rotation, and large-scale circulations. SI will enable us to understand the various effects of magnetic fields of stars, the dynamos that generate these fields, and the internal structure and dynamics of the stars in which these dynamos operate. The ultimate goal of the mission is to achieve the best-possible forecasting of solar activity as a driver of climate and space weather on time scales ranging from months up to decades, and an understanding of the impact of stellar magnetic activity on life in the Universe. The road to that goal will revolutionize our understanding of stars and stellar systems, the building blocks of the Universe. Fitting naturally within the NASA and ESA long-term time lines, SI complements defined missions, and with them will show us entire other solar systems, from the central star to their orbiting planets. In this paper we describe the scientific goals of the mission, the performance requirements needed to address those goals, and the design concepts now under study. We also note other fields of astrophysics that would benefit from a long-baseline interferometer in space and report on the current status of the mission concept development efforts.
1. Introduction

The primary science goals of the SI mission are to study spatio-temporal stellar magnetic activity patterns in a sample of stars covering a broad range of activity, in order to: 1) understand the underlying dynamo process(es) and thereby enable improved forecasting of solar activity on time scales of days to centuries, 2) understand the impact of stellar magnetic activity on astrobiology, 3) enable astroseismology (acoustic imaging) to measure internal stellar structure and rotation and their relationship to the dynamo, and 4) complete the assessment of external solar systems by imaging the central stars of systems in which the IR-interferometry missions [Terrestrial Planet Finder (TPF), IRSI/Darwin, Planet Imager (PI)] find and image planets.

2. Science Requirements and Performance Goals

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: surface imaging to detect and monitor the evolution of active regions, and astroseismology (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 thereby provide robust observational constraints on dynamo theories.

The design requirements for imaging of stellar surface activity include the acquisition of ultraviolet (UV) images (with \(\sim\)1000 pixels over the stellar surface) 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 the surface wherever it is penetrated by strong magnetic fields, making them ideal activity diagnostics. Modest integration times (\(\sim\)hours for dwarfs to days for giants) are required to avoid smearing of images due to rotation, proper motions, and activity evolution. 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, and low-resolution imaging to measure non-radial resonant waves (\(\sim\)30-100 total resolution elements over the stellar surface). Flexible interferometer configurations are required in both modes.

3. Strawman Mission Concept

The current leading architecture concept for Stellar Imager 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 array elements on "mirrorsats". Those elements direct light to an image-plane beam combination facility in a hub at the prime focus, as shown in Figure 1. This design will provide: an angular
resolution of 60 and 120 micro-arcseconds 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 C IV (100,000 K) and MgII h&k (10,000 K), and broadband observations in the near-UV or optical continuum (formed at 3,000-10,000 K). SI 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 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 Lagrange point L2, which has both a small and very well characterized gravity gradient that permits precision formation flying and which should be accessible in the 2020 time frame for servicing and upgrade by robotic and/or manned missions.

3.1. Place in NASA/ESA Strategic Roadmaps

SI is on the strategic path of NASA Origins and ESA interferometry missions. It is a stepping stone towards crucial technology: SI is comparable in complexity to the TPF and Darwin nulling-IR-interferometers, and it may serve as a useful pathfinder for the Planet Imager. SI addresses science goals of three NASA Office of Space Science Themes: understand why the Sun varies (Sun Earth Connection), understand the origin of stars, planetary systems, and life (Origins), understand the structure and evolution of stars (Structure and Evolution of the Universe). It is complementary to the planetary imaging interferometers. TPF, IRSI/Darwin, and PI 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 those planets. TPF, SI, IRSI/Darwin, and PI together provide complete views of other solar systems.

3.2. SI and General Astrophysics

A long-baseline interferometer in space could benefit many fields of astrophysics (cf., Bely et al. 1996). Potential targets include: Active galactic nuclei – the
transition zone between broad-line regions and narrow-line regions, origin and orientation of jets; *Quasi-stellar objects and black holes* — close-in structure, radiation from accretion processes; *Supernovae* — close-in structure; *Stellar interiors* — internal structure of stars outside solar parameters; *Hot stars* — hot polar winds, non-radial photospheric pulsations; *Envelopes and shells of Be-stars*; *Spectroscopic binary stars* — observe companions and orbits, determine stellar properties, perform key tests of stellar evolution; *Interacting binary stars* — resolve mass-exchange, dynamical evolution and accretion, study more efficient dynamos; *Cool, evolved giant and supergiant stars and long-period and semi-regular variable stars* — spatio-temporal structure of extended atmospheres/winds and shocks; and * Extrasolar planet detection* — via transits.

3.3. Enabling Technologies

Stellar Imager will rely on a number of critical technologies, including: precision formation flying, lightweight mirror technology, coarse ranging and array alignment, on-board autonomous computing and control systems, and closed loop optical control to maintain array alignment based on the science data.

Study of these technologies is ongoing at GSFC, JPL, various universities, and in industry, and significant leveraging and cross-fertilization will occur across projects [e.g., with the Next Generation Space Telescope (NGST) and TPF]. Series of testbeds are in operation or are under development at GSFC, including the: Wavefront Control Testbed to study image-based optical control methods for NGST, Phase Diverse Testbed to study extended scene phase diversity optical control with moving array elements, Wide-Field Imaging Interferometry Testbed to study extending the field of Michelson imaging interferometers, and the Fizeau Interferometry Testbed to study closed-loop control of an array of elements, as well as assess and refine technical requirements on hardware, control, and imaging algorithms. Studies of the full SI mission as well as pathfinder concepts continue in GSFC’s Integrated Design Center.

4. Summary/Status

SI is currently included in the far-horizon NASA Sun-Earth Connection Roadmap. The mission concept continues to be developed by GSFC in collaboration with LMATC, NRL/NPOI, STScI, and the University of Maryland. Further information on the mission can be found on the internet at the following URL: http://hires.gsfc.nasa.gov/~si. 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@imsal.com) with your comments and suggestions.

References