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The Stellar Imager (SI) – A Mission to Resolve Stellar Surfaces, Interiors, and Magnetic Activity

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Abstract. The Stellar Imager (SI) is a space-based, UV/Optical Interferometer (UVOI) designed to enable 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and of the Universe in general. It will also probe via asteroseismology flows and structures in stellar interiors. SI will enable the development and testing of a predictive dynamo model for the Sun, by observing patterns of surface activity and imaging of the structure and differential rotation of stellar interiors in a population study of Sun-like stars to determine the dependence of dynamo action on mass, internal structure and flows, and time. SI's science focuses on the role of magnetism in the Universe and will revolutionize our understanding of the formation of planetary systems, of the habitability and climatology of distant planets, and of many magneto-hydrodynamically controlled processes in the Universe. SI is a "Landmark/Discovery Mission" in the 2005 Heliophysics Roadmap, an implementation of the UVOI in the 2006 Astrophysics Strategic Plan, and a NASA Vision Mission ("NASA Space Science Vision Missions" (2008), ed. M. Allen). We present here the science goals of the SI Mission, a mission architecture that could meet those goals, and the technology development needed to enable this mission. Additional information on SI can be found at: `http://hires.gsfc.nasa.gov/si/`.

1. Science goals of the mission

The Stellar Imager (SI) is a NASA Vision Mission (VM), developed by an international team, to study 1) solar and stellar magnetic activity and their impact on space weather, planetary climates, and life and 2) magnetic processes in general and the roles they play in the origin and evolution of its structure and the transport of matter throughout the Universe

SI's primary science goal will be addressed by observing and measuring spatial and temporal stellar surface magnetic activity patterns through ultra-high angular resolution (sub-milliarcsec) UV imaging, and by measuring via disk-resolved asteroseismology the internal structure and flows that produce it, in a sample of stars covering a broad range of masses, radii, and activity levels. These observations will lead to an improved understanding of the underlying dynamo process(es) and thus enable improved forecasting of solar (and stellar) activity on time scales of days to centuries. This, in turn, will facilitate an improved understanding of the impact of stellar magnetic activity on life on earth and on exo-planets found around more distant stars.

1.1. Key Questions

There are a number of important questions that SI needs to address in order to achieve its goal of understanding dynamos and magnetic activity, including:

- what do the internal structure and dynamics of magnetically active stars look like?
- what sets the dynamo strength and pattern in individual stars, from dwarfs to supergiants?
- how can active stars form polar spots?
- what can we expect next from the Sun, on time scales from hours to centuries?
- why do 2 in 3 Sun-like stars show no cycles?
- what causes solar-type "Maunder minima" or "grand maxima"?
- how does stellar activity drive all aspects of "space weather" and affect planetary climates and life around solar-type and evolved stars?
- how do dynamos evolve with time?
- how do dynamos differ in dwarf vs. giant stars?

Only with the answers to such questions will it be possible more fully to constrain theoretical dynamo models and enable true forecasts of future solar and stellar magnetic activity. These questions will be addressed by spatially resolving stellar disks to map evolving atmospheric activity as a tracer of dynamo patterns and by asteroseismic probing (to at least degrees of order 60) of internal stellar structure and flows in stars of various masses, radii, and activity levels. Such a "population study" will provide answers far more rapidly than by continuing our close-up observations of the Sun over many decades as we observe it moving through the multiple and different activity cycles that are needed to obtain a full set of observational constraints - and some of these data would never be obtainable from the Sun alone, as it is only one example of how dynamos operate and magnetic activity is produced.

2. Proposed mission architecture

2.1. Design requirements

SI's science goals require it to have the following capabilities:

- Wavelength coverage: 1200-6600 Å
- access to UV emission lines from Ly-alpha 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 saves a factor 2-4 vs. optical, active regions 5 times larger)
    - ~10 Å UV pass-bands, to isolate, e.g., C IV (formed at 100,000 K) & Mg II h&k (10,000 K)
- broadband, near-UV or optical (corresponding to temperatures of 3,000-10,000 K) for high temporal resolution, spatially-resolved asteroseismology to resolve internal structure
- angular resolution of 50 micro-arcsec at 1200 Å (120 mas at 2800 Å)
    - resolution of ~1000 pixels over the surface of nearby (~4 pc) dwarf stars and over the surface of the many giant and supergiant stars within ~2 kpc
- energy resolution/spectroscopy possible for detected structures
- a long-term (~10 year) mission to study stellar activity cycles: individual telescopes/hub(s) must be able to be refurbished or replaced

2.2. "Strawman" design

The VM Study developed a baseline mission design that satisfies all of the above requirements. This design is for a space-based, UV-Optical Fizeau Interferometer with 20-30 one-meter primary mirrors, mounted on formation-flying "mirrorsats" distributed over a parabolic virtual surface whose diameter can be varied from 100 m up to as much as 1000 m, depending on the angular size of the target to be observed. The individual mirrors are fabricated as ultra-smooth, UV-quality flats and are actuated to produce the extremely gentle curvature needed to focus light on the beam-combining hub that is located at the prime focus from 1 - 10 km distant. The focal length scales linearly with the diameter of the primary array, i.e., a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array to a focal length of 10 km. The typical configuration has a 500 m array diameter and 5 km focal length. A one-meter primary mirror size was chosen to ensure that the primary stellar activity targets can be well observed with good signal/noise. The mirrorsats fly in formation with a beam-combining hub in a Lissajous orbit around the Sun-Earth L2 point. The satellites are controlled to mm-micron radial precision relative to the hub and the mirror surfaces to 5 nm radial precision, rather than using optical delay lines inside the hub for fine tuning the optical path lengths. A second hub is strongly recommended to provide critical-path redundancy and major observing efficiency enhancements. The observatory may also include a "reference craft" to perform metrology on the formation, depending on which metrology design option is chosen. The VM Study identified two launch concepts that are quite feasible, assuming 1m diameter primary mirrors, with current vehicles. Depending on the number of hubs to be launched initially, one or two Delta IV launches will suffice to lift the entire observatory to Sun-Earth L2.

Additional details on the architectural concept can be found in [1] and in the complete VM report at `http://hires.gsfc.nasa.gov/si/`.

3. Technology development needed to enable the mission

The major technology challenges to building SI are:

- 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 sensing and control to 10's of micro-arcsec
    - positioning mirror surfaces to 5 nm
    - variable, non-condensing, continuous micro-Newton thrusters
- precision metrology over multi-km baselines
    - 2nm if used alone for path length control (no wavefront sensing)
    - 0.5 microns if hand-off to wavefront sensing & control for nm-level positioning
    - multiple modes to cover wide dynamic range
- wavefront sensing and real-time, autonomous analysis and control
- methodologies for ground-based validation of distributed systems
- additional challenges (perceived as easier than the above)
    - mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, and test
    - long mission lifetime requirement
    - light-weight UV quality mirrors with km-long radii of curvature, using active deformation of flats
    - larger format (6 K × 6 K) energy resolving detectors with finer energy resolution (R=100)

The major challenges in this list are being attacked via a number of ground-based testbeds [2] to develop and assess precision (to the cm level) formation flying algorithms and closed-loop optical control of tip, tilt, and piston of the individual mirrors in a sparse array, based on feedback from wavefront analysis of the science data stream. The GSFC Fizeau Interferometer Testbed (FIT) is developing closed-loop optical control of a many-element sparse array, with 7-elements in Phase 1, and 18-elements in Phase 2. GSFC, MIT, and MSFC are collaborating on an experiment, the Synthetic Imaging Formation Flying Testbed (SIFFT), utilizing the MIT SPHERES hardware on the MSFC Flat Floor facility to test cm-level formation flying algorithms. The GSFC Formation Flying Testbed (FFTB) is a software simulation facility that has been used to develop deployment of array spacecraft and the multi-stage acquisition of target light from the individual mirrors by the beam-combiner. In addition, there are relevant high precision metrology development efforts at SAO [3] and JPL [4]. The ultimate goal of all these efforts is to demonstrate staged-control methodologies covering over 12 orders of magnitude, from km down to nm scales. We are also studying alternative optical designs for SI to optimize its imaging and spectral energy resolution capabilities [5].

The results from these testbeds and studies will be combined with experience from existing ground-based interferometers, to enable a small, space-based UV/Optical Pathfinder mission, which will use a small number of elements (3-5) with smaller baselines (20-50m) and frequent array reconfigurations (to fill in the Fourier uv-plane and enable high quality imaging) to both accomplish important new science and demonstrate in space the technologies needed for the full-up SI. One or more such Pathfinder missions (others are possible in the IR and X-ray as pathfinders for MAXIM/Black Hole Imager (BHI) and the Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) will lay the ground-work for the long-baseline, Strategic "Vision" Missions that will do true high angular resolution interferometric imaging, including SI, Life Finder, and Planet Imager.

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