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Dynamos, Asteroseismology, and the Stellar Imager

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Abstract

The ultra-sharp images of the Stellar Imager[1] (SI) will revolutionize our view of many dynamic astrophysical processes: The 0.1 milli-arcsec resolution of this deep-space telescope will transform point sources into extended sources, and simple snapshots into spellbinding evolving views. SI's science focuses on the role of magnetism in the Universe, particularly on magnetic activity on the surfaces of stars like the Sun and on the subsurface flows that drive this activity. SI's prime goal is to image magnetically active stars with enough resolution to map their evolving dynamo patterns and their internal flows. By exploring the Universe at ultra-high resolution, SI will also revolutionize our understanding of the formation of planetary systems, of the habitability and climatology of Earth as well as distant exoplanets, and of many magneto-hydrodynamically controlled structures and processes in the Universe.

Introduction

The Stellar Imager (SI) is a UV-optical, space-based interferometer designed to enable 0.1 milli-arcsecond (mas) spectral imaging of stellar surfaces and asteroseismic exploration of stellar interiors, and the high-resolution exploration of the Universe in general. The key science goals of the SI mission are (1) to study the evolution of stellar magnetic dynamos from the very formation of stars and planetary systems onward to the final stages of stellar evolution; (2) to complete the assessment of external solar systems begun by the planet-finding and imaging missions by observing their central stars in detail; and (3) to study the Universe at ultra-high angular resolution from the internal structure and dynamics of stars and interacting binaries to extreme conditions in, e.g., active galactic nuclei and in black hole environments.

The resolving power of SI makes it a unique tool for a variety of scientific research areas in general astrophysics, including magnetically active stars, stellar interiors in stars outside solar parameters, infant star-disk systems, hot stars, cool giant and supergiant stars, supernovae and planetary nebulae, interacting binaries, active galactic nuclei, quasars, black-hole environments, etc. Here, we focus on stellar magnetic activity, and on the internal stellar dynamics that drives dynamos in the Sun and stars.

Stellar Magnetic Activity

The recognition of the importance of the Sun's variability has led to the development of an International Living With A Star program and its research infrastructure. At the core of that program is the Sun's magnetic field: what causes the Sun to be magnetically active, and how can we develop reliable forecasting tools for this activity and the associated space weather and climate changes on Earth? The Stellar Imager aims to make crucial contributions to this

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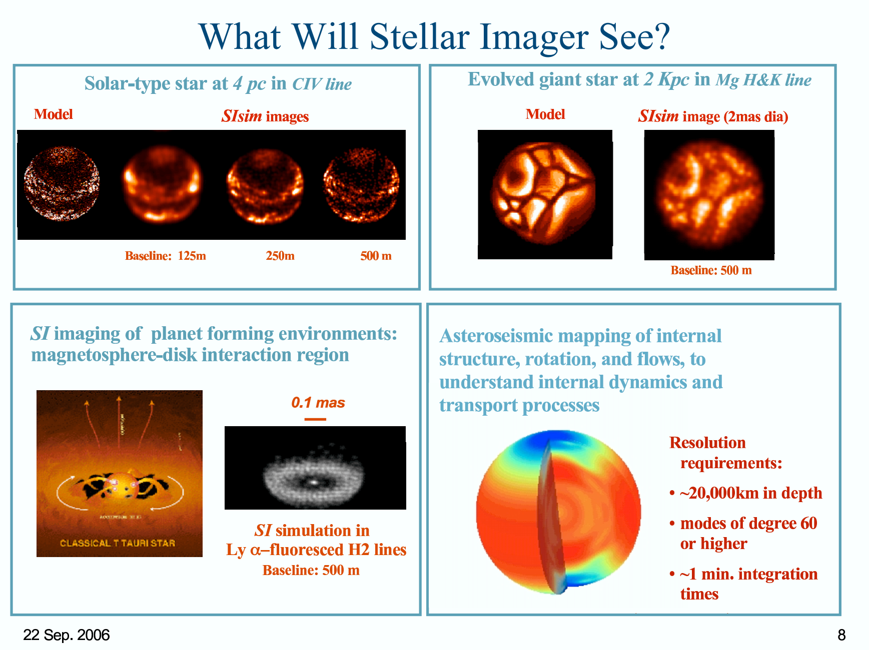
[1] See `http://hires.gsfc.nasa.gov/si/` for details on the Stellar Imager mission.



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

Asteroseismic mapping of internal structure, rotation, and flows, to understand internal dynamics and transport processes

Resolution requirements:

- ~20,000km in depth
- modes of degree 60 or higher
- ~1 min. integration times

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Figure 1: Simulations of SI's imaging capabilities for 30 mirror elements, and a visualization of stellar interior flows.

field, warranting its status as a Landmark Discovery Mission in the 2005 roadmap for NASA's Heliophysics Division.

The principal cause of all solar variability is its magnetic field. This intangible and unfamiliar fundamental force of nature is created in the convective envelope of the Sun by a process that we call the dynamo. There is at present no quantitative model for stellar dynamos that is useful to forecast solar activity or even to establish the mean activity level of a star based on, say, its mass, age, and rotation rate. The nonlinear differential equations for the coupling of the vectors of turbulent convection and magnetic field cannot be solved analytically. Nor can the cycle dynamo be simulated numerically in its entirety; full numerical coverage would require some 10^{18} grid points, which is a factor of order a billion beyond present computational means. Hence, both analytical and numerical studies necessarily make approximations that simplify or ignore much of the physics. Furthermore, even the approximating models are of a richness and diversity that there is no consensus on the model properties, or even on the set of processes that are important in driving the dynamo. Numerical research will undoubtedly make significant advances in the coming years, but only the comparative analysis of many Sun-like stars with a range of activity levels, masses, and evolutionary stages will allow adequate tests of complex dynamo models, validation of any detailed dynamo model, and exploration of the possible spatio-temporal patterns of the nonlinear dynamo.

The studies of average activity levels of stars have helped us piece together what some of the essential ingredients to dynamo action are on the largest scales. For example, we know that a dynamo associated with stellar activity operates in all rotating stars with a convection zone directly beneath the photosphere. In single stars, the dynamo strength varies smoothly,

Table 1: SI mission and performance parameters

Parameter	Value	Notes
Max. mirror separation	$B =$ 100-1000 m	500 m typical
Effective focal length	1-10 km	Scales with B
Diameter of mirrors	1-2 m	Up to 30 mirrors
Wavelength coverage	λ 1200-3200Å	Wavefront sensing
	λ 3200-5000Å	in optical only
Spectral resolution	10Å(lines);100Å(cont.)	
Angular resolution	50 μas-208μas	Scales with λ/B
Optical surfaces	actuated to μm-nm	
Phase corrections	to $\lambda/10$	for path lengths
Time to image	$<$ 5 h for solar type	Surface imaging
stellar surface	$<$ 1 d for supergiant	
No. of pixels on star	$\sim$ 1000	Sun-like at 4 pc.
Time to map int. flows	Rotation period	Set by target
Seismology cadence	1 minute	Internal structure
Minimum field of view	$>$ 4 milli-arcsec	
Min. detectable flux	$5. \times 10^{-14}$ ergs/cm^2/s	10Å band at 1550Å
Operational orbit	200×800 Mm; 180 d	at Sun-Earth L2
Operational lifetime	5 y (req.) - 10 y (goal)	
Accessible Sun angle	$70^\circ \leq \theta \leq 110^\circ$	Entire sky in 180 d
Combiner dry mass	1455 kg	1 req.; 2 optional
Mirrorsat dry mass	65 -120 kg	up to 30 satellites
Reference platform	200 kg	
Total propellant	750 kg	for operations
S/C control	mm-cm level	Formation flying
Pointing control	3 μas up to 1000 s	

and mostly monotonically, with rotation rate, at least down to the intrinsic scatter associated with stellar variability. It also depends on some other unknown stellar property or properties. For main sequence stars, for example, the primary factor in determining activity resembles the convective turnover time scale at the bottom of the convective envelope. But no such dependence holds if we test the relationship on either evolved stars or on tidally-interacting compact binary systems. Apparently, other parameters, as yet unidentified, play a role, such as surface gravity and tidal forces.

The variations of stellar and solar activity on time scales of years also remain a mystery. The Sun shows a relatively regular heartbeat with its 11-year sunspot cycle, even as cycle strength and duration are modulated. Such a pattern is not the rule among the cool main-sequence stars, however. Instead, we find a variety of patterns in their activity, in which only one in three of these stars show cyclic variations like those of the Sun. For truly active stars, various variability patterns exist, but generally no unambiguous activity cycle is seen.

It would take hundreds of years to validate a solar dynamo model using only observations of the Sun, given its irregular 11-year magnetic heartbeat and the long-term modulations. Key to successfully navigating the route to a workable, predictive dynamo model is the realization that in order to understand the solar dynamo, we need a population study; that is, we need to study the dynamo-driven activity in a sample of stars like the Sun, and compare it to observations of younger stars, older stars, and stars in binary systems, etc. Thus, the SI will enable us to test and validate solar dynamo models within a decade, rather than requiring a century or more if we used only the Sun.

The potential for a breakthrough in our understanding and our prediction ability lies in spatially-resolved imaging of the dynamo-driven activity patterns on a variety of stars. These patterns, and how they depend on stellar properties (including convection, differential rotation and meridional circulation, evolutionary stage/age), are crucial for dynamo theorists to explore the sensitive dependencies on many poorly known parameters, to investigate bifurcations in a nonlinear 3-dimensional dynamo theory, and to validate the ultimate model.

Direct, interferometric imaging - the goal of the Stellar Imager - is the only way to obtain the required information on the dynamo patterns for stars of Sun-like activity. Alternative methods that offer limited information on spatial patterns on much more active stars fail for a Sun-like star: a) rotationally-induced Doppler shifts in such stars are too small compared to the line width to allow Zeeman-Doppler imaging, b) the activity level is insufficient to lead to significant spectral changes associated with magnetic line splitting, c) rotational modulation measurements leave substantial ambiguities in the latitude distributions, locations and sizes of spots, and cannot be used to measure dispersal of field across the stellar surface. The direct imaging by SI of stellar activity will overcome these problems. Equally importantly, the asteroseismic observations planned with SI will determine the internal properties of stellar structure and rotation, thus directly providing crucial information relevant to the physical operation of the dynamo mechanism.

Imaging magnetically active stars and their surroundings will also provide us with an indirect view of the Sun through time, from its formation in a molecular cloud, through its phase of decaying activity, during and beyond the red-giant phase during which the Sun will swell to about the size of the Earth's orbit, and then toward the final stages of its evolution as a Planetary Nebula and a white dwarf relic.

Asteroseismology: from dynamo to fundamental physics

The SI mission will allow us not only to image the surfaces of stars, but also to sound stellar interiors using spatially resolved asteroseismology to measure internal structure, differential rotation, and large-scale circulations; this will provide accurate knowledge of stellar structure and evolution and complex transport processes, and will impact numerous branches of (astro)physics.

Helioseismology has given us an extremely detailed view of the solar interior. These results are of great importance to our understanding of the structure and evolution of stars, and of the physical properties and processes that control this evolution. At the time of the launch of the SI, seismic investigations of other stars will have been undertaken by several space missions, including MOST and COROT. However, a number of key issues will remain open. These preceding missions will only observe low-degree modes, through intensity variations in light integrated over the stellar disks. Such point-source observations will provide information about the global properties of solar-like stars, which allows the study of global structure, including, e.g., gravitational settling of helium and large-scale mixing processes. SI observations, however, will allow us to expand the discovery space far beyond that: modes of degree as high as 60 should be reachable with an array of $N = 10$ elements, increasing as N^2 for larger arrays. By analogy with the Sun, in solar-like stars this will allow inferences with good radial and reasonable latitude resolution to be made in the radiative interior and the lower part of the convective envelope, for both structure and the patterns and magnitudes of the differential rotation with depth and latitude. With a careful choice of target stars SI observations will allow us to obtain such detailed information about the interiors of stars over a broad range of stellar parameters, in terms of mass, age and composition.

Studies of the internal rotation as a function of mass and age will provide unique information about the evolution of stellar internal rotation with age, in response to the activity-driven angular-momentum loss in stellar winds. This will provide stringent constraints on models of the rotational evolution, elucidating the processes responsible for transport of angular momentum in stellar interiors; these studies are also fundamental to the understanding of the dynamo processes likely responsible for stellar activity. By correlating the rotation profile with the profile of the helium abundance, as reflected in the seismically inferred sound speed, an understanding can be achieved of the rotationally-driven mixing processes in stellar interiors. This is of great importance for calibrating the primordial abundances in the Universe as well as to the improvement and validation of stellar evolution models. For example, the data will provide constraints on the convective overshoot at the base of the convective envelope which also contributes to the mixing. The resulting understanding can then be applied to the mixing and destruction of lithium, finally providing the means to relate the observed lithium abundance in old halo stars to the primordial lithium content of the Universe. For stars slightly more massive than the Sun the data, combined with the more extensive data on low-degree modes likely available at the time from earlier missions, will allow detailed investigations of the properties of convective cores and related internal mixing; an understanding of these processes is essential to the modelling of the evolution of massive stars, leading to the formation of supernovae.

The initial trade-off studies performed described in the Vision Mission study report[1] will need to be complemented by others to balance the scientific needs with the overall SI design and operations. Here, we point out that at a minimum we can say that $n \sim 9$ optical elements are needed to adequately measure the magnitude of the differential rotation, with mapping resolution increasing rapidly with n:

The minimum number of mirror elements required for SI follows from the need to measure the differential rotation to better than a fraction f of the stellar rotation period P. An n-element interferometer that can observe in k independent optical channels, can measure sectoral modes up to no more than azimuthal order $m = kn(n-1)/4$. For a desired frequency resolution of mf/P Hz, the observing interval should exceed $4P/fm$. When SI observes a full rotation in order to complete its surface mapping, this results in $n \gtrsim 2/\sqrt{fk}$, so that for, say, $f = 0.02$, $n \gtrsim 9$. Increasing the number of interferometer elements allows a shorter integration period needed to measure internal rotation rate, although it must necessarily remain a substantial fraction of the rotation period in order to be able to separate the frequencies in Fourier space.

The asteroseismic resolution that can be achieved at a given location within a star approximately equals the local wavelength $\lambda = c_s/\nu$, where c_s is the sound speed and ν is the cyclic frequency. Thus the resolution improves from the stellar centre to the surface as the sound speed decreases. The best resolution is obtained at the lower turning depth of the most shallowly penetrating modes for given ν, i.e., those with highest azimuthal order m. There, near the surface, the resolution is approximately $\lambda \approx 2\pi R_*/m$. For an SI design with $n = 9$ and $k = 3$, we thus find a depth resolution of $\sim$81 000 km, or 40% of the depth of the convective envelope in a Sun-like star, which poorly constrains differential rotation with depth within the envelope. For an SI design with with $n = 30$ and $k = 3$, the depth resolution is $\sim$ 7000 km or $\sim$ 3%, so that the differential rotation can be mapped accurately with depth throughout the envelope.

Within the total observing period, the net fraction of the time spent on the target star must exceed $\sim$ 50%, although alternating intervals of $\sim$ 12 h on a pair of stars nearby on the sky would suffice; that strategy would double the number of stars that can be studied in this way.

Mission architecture

The current baseline architecture concept for SI (summarized in Table 1) is a space-based, UV-optical Fizeau interferometer with up to 30 one-meter primary mirrors, mounted on formation-flying mirrorsats, distributed over a parabolic virtual surface with a diameter that 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 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: a 100 m diameter array corresponds to a focal length of 1 km and a 1000 m array with 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. Sizes up to two meters may be considered in the future, depending on the breadth of SI science targets, e.g., some fainter extra-galactic objects may need larger mirrors, but those will come at a cost to the packaging for launch, the number of launches needed, and total mission cost.

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 (see full Vision Mission study report at the SI home page[1] for more details).

The full SI mission may be built up by starting with a small number of optical elements, perhaps utilizing both interferometry and high-resolution spectroscopy. Adding optical elements increases image quality and time resolution.

SI status, technology roadmap, and timeline

SI is currently a mission concept that has been listed in three successive strategic planning documents of the Sun-Earth Connections (now Heliophysics) Division of NASA's Science Mission Directorate, most recently as a Landmark Discovery Mission, and is mentioned in the 2005 roadmap of the Exploration of the Universe Division as a possible "Pathways to Life Observatory."

SI's scientific rationale needs to be further developed to demonstrate its unique potential for studying the multitude of potential targets in the Universe. Its focus on dynamos and internal flows of Sun-like stars requires further evaluation of its discovery potential by imaging and asteroseismology. To meet those demands, we have the support of an international team of experts in a growing Mission Concept Development Team[1].

Many spacecraft engineering challenges exist which are a natural consequence of the defined science goals of the SI mission. Among the most significant, we identify telescope pointing, formation flying and mirror configuration, wavefront sensing and metrology, exposure-time limitations, and mission lifetime. SI shares these challenges with other missions in NASA's strategic plans; SI can therefore benefit from the studies performed, and expertise developed for its precursor missions. Rapidly advancing technologies may enable an SI precursor mission by 2015 and the full mission by 2025.

DISCUSSION

Roxburgh: about 1.5 years ago, there was a sketch of a project submitted to ESA in response to their call for ideas for of their Cosmic Vision 2015 program, which has in fact been written up in the COROT book by Claude Catala.

Moskalik: what kind of budget do you envision for this kind of project? 100 million dollars?

Schrijver: We are talking about 10 - 30 spacecraft that would each cost at least 5 - 10 million Euro, plus a beam combiner, launch, etc. It's not cheap. But for a stepping stone mission we have to ask for something that's of the order of half a billion. If you go to the full scale thing, it's going to be 2 - 4 times that. It may be less than JWST, but it's not a cheap mission.

Fossat: this morning I showed the concept of a photometric interferometer of thirty-nine telescopes in the Antarctic. Doing the same in space seems to be extremely difficult to me.

Schrijver: it doesn't matter how we are going to create an interferometer of this type. We need to come up with appealing science reasons from this entire community to make any of them happen because we compete against people who are talking about the age of the universe, the nature of dark matter and dark energy, the end of stars and formation of planetary systems. We need to demonstrate and march as united as we can and then see what we can get.