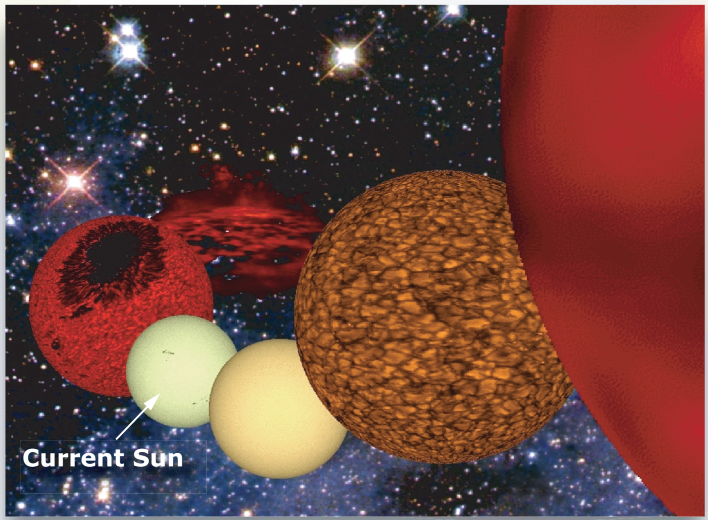
SI the stellar imager

A UV/optical interferometer in space to image dynamo activity of stars and to survey the universe and its constituents

The evolution of the Sun over a period of 10 billion years, from a protostellar disk to a red giant star. Magnetic activity plays a role from the formation of the star and its planetary system through most of its main-sequence life.



National Aeronautics and Space Administration

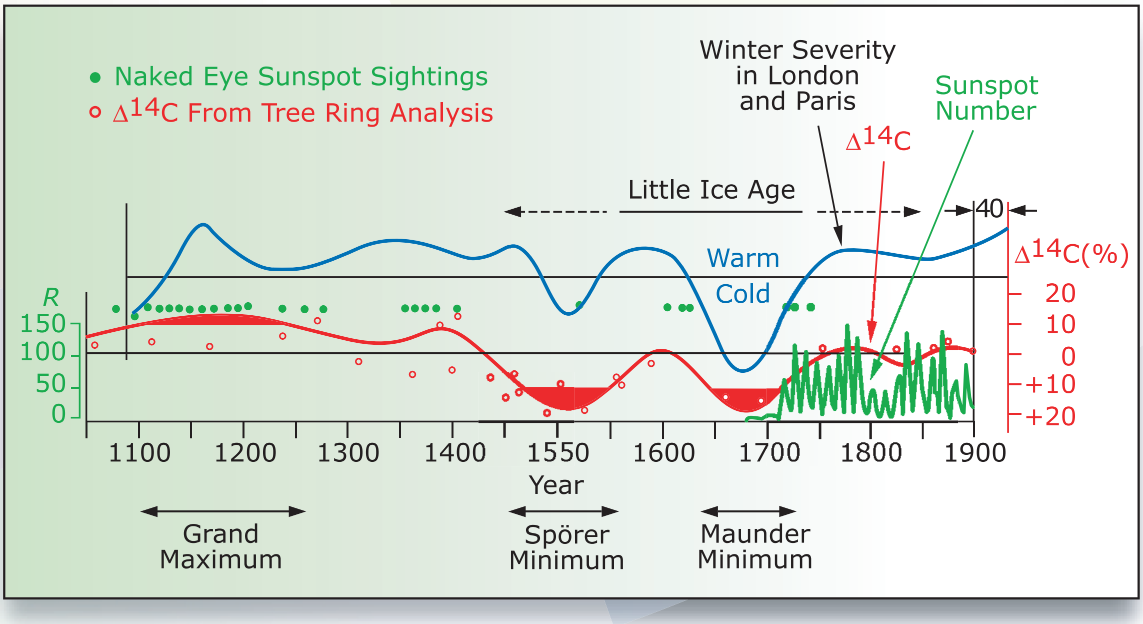
Primary Science Goals for the Stellar Imager

The Stellar Imager (SI) is a mission 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 to decades, and an understanding of the impact of stellar magnetic activity on astrobiology and life in the universe. The road to that goal will revolutionize our understanding of stars and stellar systems, the building blocks of the universe.

Most people rarely give the Sun a second thought. We do not question its presence or its apparent stability as we see it traverse the sky every day. The Sun is, however, a variable star. Its variability affects society by modulating Earth's climate. It also affects our technology, upon which we are becoming ever more reliant: eruptions on the Sun interrupt communications, affect navigation systems, cause radiation that may be harmful to astronauts and airline passengers, and occasionally push power grids to fail. The cause of this variability is the Sun's magnetic field. This intangible and unfamiliar fundamental force of nature is created in the depths of the Sun by a process that we call the dynamo.

The dynamo is one of the greatest mysteries in astrophysics. There is at present no model for the dynamo that can be used to forecast the Sun's activity on the time scale of months to decades. And yet, historical records show that the Sun can change its activity significantly, becoming more or less active at different times. When activity decreases, the Sun becomes somewhat dimmer. This happened, for example, in the 17th Century when it caused the Little Ice Age. Increased activity, such as apparently happened during the medieval Grand Maximum, may cause a warm spell, and is associated with an increase in the frequency of space storms, and in the ultraviolet radiation that is harmful to life on Earth.

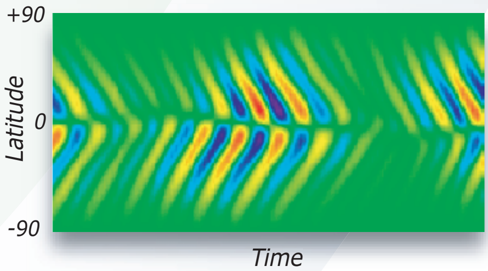
The solar dynamo operates throughout the outermost 200,000 km of the solar interior, in and just below the



Solar activity is correlated with changes in Earth's climate, but the nature of that correlation is not yet understood. Understanding it is the prime driver of NASA's Living With a Star Program.

convective envelope. The vastness of this volume relative to the smallest relevant scales precludes a full numerical model. There is at present no generally accepted dynamo model. In fact, the experts do not even agree on where most of the dynamo action occurs within the stellar interior, or which are the key processes involved. Approximate models are in development, but need to be tested before they can be used to guide policy decisions related to climate change.

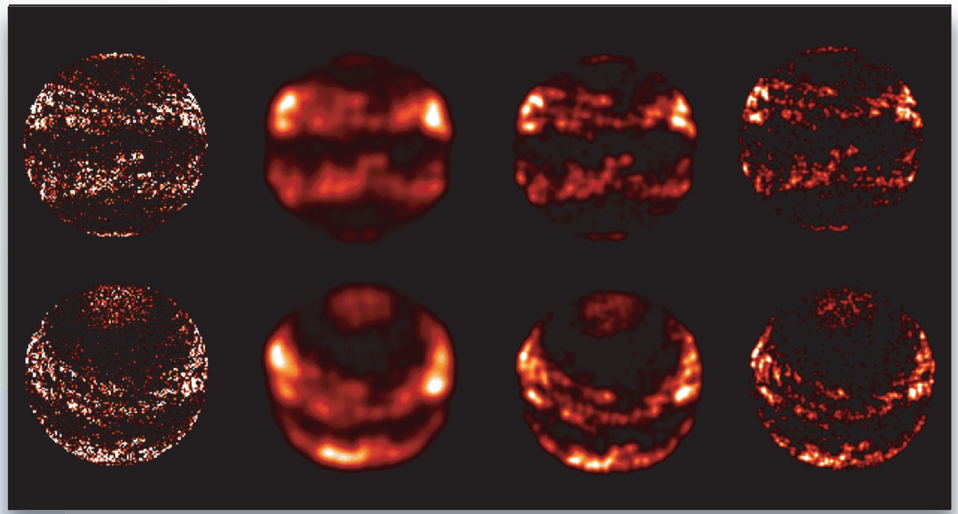
Testing dynamo models for the Sun by observing only the Sun, with its irregular magnetic heartbeat of 11 years and the significant long-term modulations on it, would take too long. The only alternative is to study a sample of stars like the Sun.



A latitude-time diagram of the activity pattern for a model dynamo. The shape of this pattern is a key discriminant between models. SI will allow us to determine these patterns for dozens of stars, and the flows associated with them.

Apart from the brightness variations that tell us about the variability of stellar activity, the most important information on the dynamo lies in the surface patterns of the magnetic field. These patterns, and how they depend on stellar properties, are crucial constraints for dynamo theorists to explore sensitive dependencies on many poorly known parameters and are essential for the validation of an ultimate model.

Direct, interferometric imaging is the only way to obtain adequate information on the dynamo patterns for other stars with Sun-like activity.



The potential of the Stellar Imager: Model CIV 1550 Å images of a star like the Sun (left) and simulated interferometric images for maximum baselines of 125 m, 250 m, and 500 m (2nd-4th columns). The top and bottom rows show views of a Sun-like star with a rotation axis in the plane of the sky and with that axis tilted by 40°, respectively. The simulated reconstructions assume observations of a star at 4 pc with 870 baseline pairs, e.g., 2 configurations of a 30-element array or 20 configurations of a 10-element array, with 800 CLEAN iterations. (Simulations computed with SISIM, written by R. Allen and J. Rajagopal/STScI.)

Alternative methods offer limited information on spatial patterns on more active stars, but fail for the much more common Sun-like stars: rotationally induced Doppler shifts in solar stars are too small compared to the line width to allow Zeeman-Doppler imaging, the activity level is insufficient to lead to significant spectral changes associated with magnetic line splitting, and rotational modulation measurements are inherently subject to limitations that leave substantial ambiguities in the data interpretation. Interferometric imaging with SI has the added benefit that it allows asteroseismological (acoustic imaging) studies of the internal structure and rotation of stars with a resolution of ~20,000 km for a star like the Sun at 4 parsecs.

Imaging magnetically active stars and their surroundings will also provide us with a view of the Sun through time, from its formation in a molecular cloud, during its current "normal" state, through its phase of decaying activity, to its ultimate death beyond the red-giant phase when the Sun will swell to about the size of the Earth's orbit.

"What then, is a magnetic field and how does it operate in the astronomical universe to cause all the "trouble" that we have attributed to it? What is this fascinating entity that, like a biological form, is able to reproduce itself and carry on an active life in the general outflow of starlight, and from there alter the behavior of stars and galaxies?"

Eugene N. Parker, 1979

Concept of the Mission and a Pathfinder Mission

The Stellar Imager is envisioned as a UV/optical interferometer which will provide images of a sample of dozens of stars over a period of up to a decade. SI, with a characteristic angular resolution of 0.1 milli-arcseconds, represents an advance in image detail of several hundred times over that provided by the Hubble Space Telescope.

The Stellar Imager will zoom in on what today – with few exceptions – we know as point sources, revealing processes never before seen, thus providing a tool as fundamental to astrophysics as the microscope is to the study of life on Earth.

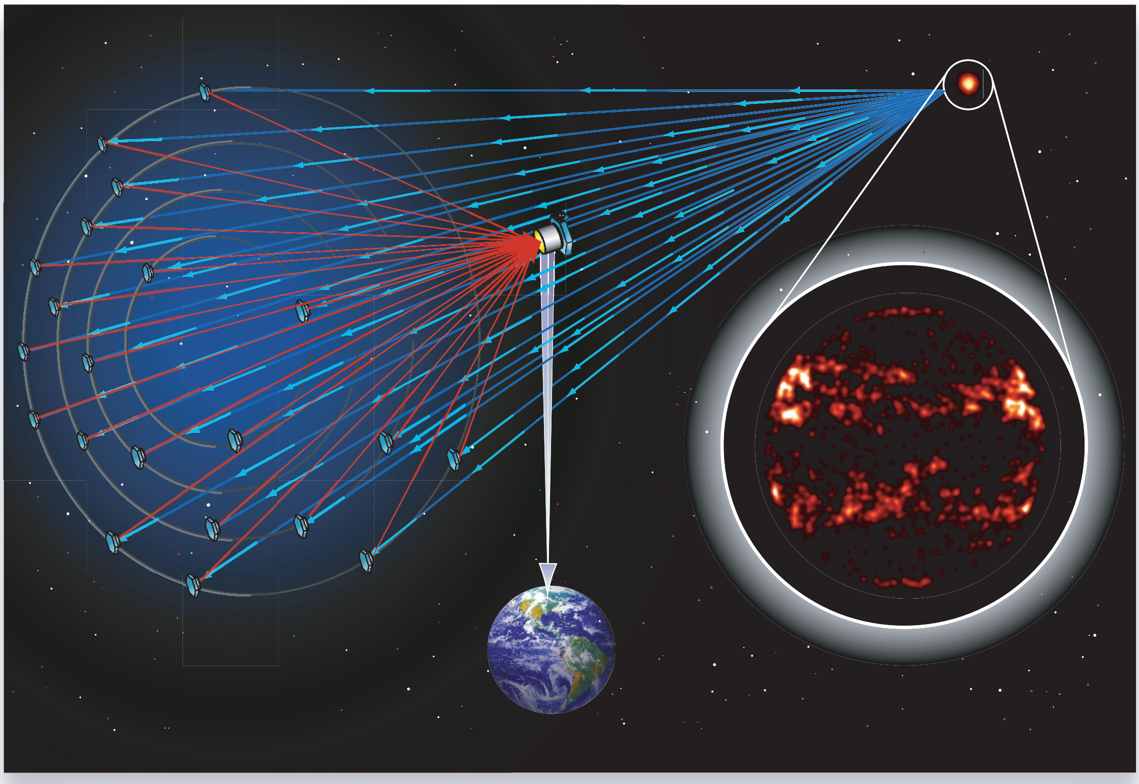
SI will image single stars and binary systems with one hundred to one thousand resolution elements across their diameter. The full-scale SI is a UV/optical aperture synthesis imager composed of at least 9, up to perhaps as many as 30, array elements on "mirrorsats'" and a central hub with focal-plane instrumentation that allows spectrophotometry in pass-bands from a few up to hundreds of Angstroms.

The full SI mission can be built up by starting with a small number of optical (array) elements, perhaps utilizing both interferometry and high-resolution spectroscopy, to observe a limited number of stars. Adding further optical elements will increase image quality and time resolution and enable the full suite of SI science. Table 1 summarizes the primary science goals and instrument requirements.

The SI mission will also sound stellar interiors using asteroseismology (by resolving light variations on the stellar disk) in order to image 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 ranging from the Big Bang to the future of the universe. *For arrays of 9 or more optical elements, asteroseismic imaging of internal structure and rotation is possible with a depth resolution of 20,000 km over the full region of dynamo operation for a star like the Sun at a distance of 4 parsecs.*

Table 1. Science goals and performance requirements for the Stellar Imager.

- Image stellar activity using emission from the outer atmosphere:
  - Image nearby main-sequence and giant stars with at least 1,000 resolution elements on their surface, in UV emission lines originating in the outer atmosphere; requires a baseline of 500 m for a star at 4 parsecs.
  - Construct images within ~1% of the stellar rotation period, i.e., ~6 hours for a star like the Sun; requires either efficient reconfiguration or many interferometer components ($\gtrsim$20), and an increasing number of interferometer components for increasing rotation rate.
  - Compile at least ~20 images within one stellar rotation; requires optimized target lists and efficient repointing.
  - Revisit stars during 3-6 month intervals, spanning ~10 yrs; requires a long operational life.
- Image stellar interiors with the asteroseismic technique of acoustic imaging:
  - Achieve 30 resolution elements on stellar disks with 1-minute time resolution, in a broad passband in the optical; requires at least 9 optical elements, with meter-class collecting areas, aligned perpendicular to the stellar rotation axis.
  - Continuous observations for approximately one rotation, with duty cycle better than ~90%; requires stable environment.



One possible architecture for the SI mission: An array of many (≥20) mirrorsats, each with a meter-class mirror, directing light to a primary hub in which the light beams are combined. A simulated observation is shown in the circle at the right. Alternative architectures utilize a smaller number of mirrorsats that are reconfigured with much greater frequency. The outer diameter of the array must be ~500 meters to enable resolution of the surface features of a typical stellar target.

Table 2. Missions contributing to the study of stellar activity.

Project	Role in Activity Studies	Technology
Stellar Imager	Dynamo patterns, Differential rotation, Internal structure, Binary interactions	UV/Optical interferometry <0.1 milli-arcsec, spatially resolved stellar seismology (asteroseismology)
NGST	Stellar mass loss, Giant chromospheres	IR imaging, 100 milli-arcsec
Space-based interferometry: STARLIGHT, SIM, TPF	–	Technology precursors
Ground-based interferometry: COAST, NPOI, Keck, CHARA, VLTI, LBT	Giant star imaging, Binary properties	Technology precursors
Eddington	Rotational modulation, Internal structure	High-precision photometry, Radial-mode seismology
FAME, GAIA	Determination of stellar properties	High-precision parallaxes
MOST, COROT	Average internal stellar structure	Unresolved astero-seismology (no spatial information)
SOHO, TRACE, Solar-B	Field dynamics, Interaction with flows	Atmospheric and vector field imaging
SOHO, SDO, GONG	Solar internal structure and dynamics	Helioseismology, Atmospheric imaging
Ground-based spectroscopy	Activity monitoring, Limited imaging	Automatic telescopes, (Zeeman) Doppler imaging

the stellar imager

General Astrophysics With the Stellar Imager

Of all the stars in the universe, only one has been seen as it truly is ... highly complex and ever changing. Yet the Sun is representative of only one of many types of stars that can be imaged with SI. Our knowledge of stars forms the foundation of our understanding of the universe. Magnetic fields affect the evolution of stars and planetary systems in all phases, from the formation of the star and its planets, to the habitability of these planets throughout the billions of years of the star's lifetime.

A long-baseline interferometer in space will benefit many fields of astrophysics. Imagine unprecedented images of active galactic nuclei, quasi-stellar objects, supernovae, interacting binary stars, supergiant stars, hot main-sequence stars, star-forming regions, and proto-planetary disks.

Table 3. The Stellar Imager fits in the national science priorities, the NASA strategic plan, the Living With a Star (LWS) initiative, and the NASA technology roadmap.

- SI is responsive to a key national priority: imaging of magnetically active stars provides the only means to validate a theory of solar magnetic activity as the driver of space weather and climate that can be achieved within a decade after deployment.
- SI meets scientific priorities identified by the NAS Astronomy and Astrophysics Survey Committee (2001). With SI we can "survey the universe and its constituents,... use the universe as a unique laboratory,... study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets," and, by focusing on the driver of space weather in time, "understand how the astronomical environment affects Earth."
- SI fits in the NASA/OSS strategic plan: it complements the LWS initiative, and shares much of the scientific and technological road that leads to other interferometers such as the Terrestrial Planet Finder, the Sub-millimeter Probe of the Evolution of Cosmic Structure, the Planet Imager, and the MicroArcsecond X-ray Imaging Mission.
- SI complements and builds on observations made by ground-based interferometers, by asteroseismology missions, NGST, and other missions (Table 2).

The Stellar Imager and the National Science Program

The Stellar Imager complements defined and proposed missions (Table 2). It fits naturally within the NASA long-term time line and meets key national science priorities, as shown in Table 3. SI is crucial to obtaining a complete picture of other solar systems, from the central stars to their orbiting planets. It also fits logically into the technology roadmap leading from interferometers like Keck and SIM to the Terrestrial Planet Finder, MAXIM, and the Planet Imager.

SI is a natural culmination of science addressed with ongoing ground-based observatories and a series of space missions (Table 2). These efforts will provide information on long-term disk-integrated variability, large-scale internal structure and evolutionary status, distances and other fundamental stellar properties, binary properties, and low-resolution surface imaging for a subset of target classes. Other missions, such as SIM and TPF, are space-based interferometers that share the technology roadmap for the Stellar Imager.

Imaging the surfaces and interiors of stars with SI constitutes a voyage of discovery and exploration that will significantly deepen our understanding of a broad range of astrophysical processes and allow verification of many model theories, thus both strengthening the foundations of our view of the universe and helping us to forecast the activity of the Sun for our society that is "Living With a Star."

The SI mission concept is being developed by NASA/GSFC in collaboration with LMMS-ATC, NRL/NPOI, UMD, and STScI. An international group of scientists serves as consultants in defining the goals and requirements of the mission. Input and participation is encouraged from all interested parties.

Additional information on the Stellar Imager can be found at: http://hires.gsfc.nasa.gov/~si/

Author Information:
Carolus J. Schrijver • schryver@lmsal.com
Lockheed Martin Advanced Technology Center, Palo Alto, CA
Kenneth G. Carpenter • kgc@stargate.gsfc.nasa.gov
NASA Goddard Space Flight Center, Greenbelt, MD