Science Objectives and Instrument Designs of the SOLAR-C Mission

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SOLAR-C Proposed mission definition



Mission: to understand solar and heliospheric magnetic activities and to develop algorithm for solar activity prediction by understanding the magnetic coupling of convection zone-photosphere-chromospheretransition region and corona

Science cases:

- 1. 3D-magnetic structure with neutral sheets
- 2. Heating of chromosphere and corona
- 3. Acceleration of fast solar wind
- 4. Prediction of solar flares
- 5. Fundamental plasma processes such as reconnection, waves, shocks, particle acceleration and turbulence
- 6. Global and local dynamo
- 7. Sun's influence to Earth climate

Key requirements:

- 1. High spatial resolution to see elemental structure inferred by Hinode
- 2. High time resolution to freeze rapidly changing chromospheric phenomena
- 3. Chromospheric magnetic observations
- 4. Seamless spectroscopic imaging observations from photosphere to corona
- 5. Wide FOV to connect local and global, and to cover AR

Imaging spectroscopy instruments:

<u>X-ray/EUV</u>: photoncounting or ultra-high resolution EUV telescopes

<u>*UV:*</u> high-throughput telescope x10 more sensitive with seamless coverage in temperature Visible: 1.5m-class telescope to obtain 3D magnetic structure from photosphere to corona with x10 more photons, and x3 resolution with high cadence



Hinode G-band

Polar faculae in G-band How to connect photosphere with upper atmosphere, detect wave propagation along magnetic field lines

Spicules are ubiquitous! But not understandable their origin!





Sunspot, formation, dynamics



Coronal heating



Phenomenological "connectivity" between the base of the corona and the chromosphere/transition region with EUV-line images

Heating and activities of hot loops with broad-band soft X-ray images

-180 -160

-140 - 120

X (arcsecs)

-100

-120

-140

X (arcsecs)

-160

-100 -80

"What corona do we want to see?"

Correspondence of low corona and chromosphere at ultra-fine scales



Science from Hinode to SOLAR-C

Hinode: 50 cm Optical telescope, EIS, and XRT

New findings and New Questions by Hinode



Magnetic fields dominate the dynamics in the chromosphere, transition region and the corona, and likely play a central role in the heating mechanisms. For understanding the heating mechanisms it is essential to carry out high accuracy and high spatial-resolution observations of magnetic fields from the photosphere to the corona, including the chromosphere.

SOLAR-C Science



To clarify the nature of these waves from the photosphere and chromosphere, and determine whether they are responsible for coronal heating and solar wind acceleration.

Determining the threedimensional structure of the solar magnetic field from the photosphere to the corona will be necessary for clarifying the many different phenomena associated with those magnetic fields to make seamless observations across the solar atmosphere, at various temperatures, of reconnectioninduced plasma flows, MHD waves, and shock waves.





How do we observationally connect these regions with such different appearances?



Photosphere

Interface region Chromosphere 2-5MK corona

Questions to determine model instrument specifications

- How do we determine chromospheric magnetic structure?
- •How do we determine coronal magnetic structure?
- Can we identify neutral sheet structures?
- Can we identify waves in chormosphere?
- •What is the smallest scale size inferred from filling factors in all layers?
- •What is the source of EIS line broadening; flows or turbulence or waves?
- •How do we confirm or reject the Parker and type-II spicule conjectures on coronal heating?

Science definition in short

 Understand the origin of the sun's dynamic atmosphere (= chromosphere and corona)

by

- Measure the magnetic field and plasma flow at the location where the magnetic action is taking place.
- Understand fundamental MHD processes taking place on the Sun (and universe)
- Understand the triggering mechanism of explosive phenomena (flare, CME,,) and predict them.

SOLAR-C model instruments

- SUVIT
 - Maximum 1.5m-class large aperture for photons and resolution
 - Equipped with *IR-detector* system for Hel observations
 - Equipped with both *spectro-polarimeter (SP) & filter-graph*
 - SP requires *IFU unit* for high cadence observations.
- EUVST (LEMUR)
 - High-throughput seamless temperature coverage
- XIT
 - EUV telescope with *very high spatial resolution*
 - *Photon counting* spectroscopy for coronal and flare plasmas



SOLAR-C



- Solar UV-Visible-near Infrared Telescope (SUVIT)
 - High resolution and high throughput allows to see thermal, dynamical, and magnetic structures in the chromosphere.
 - Large aperture optical telescope (~1.5m).
- EUVST (high troughput EUV spectroscopic telescope)
- XIT (High Resolution X-ray Imager)
- Geosynchronous orbit (TBD) for flexible science operation, good telemetry

SUVIT design policy

Employ the advantage of space.

- Advantages of space \rightarrow telescope requirement
- Constant PSF
 - → High spatial resolution (~0.1"), Diffraction limited optics
 - \rightarrow High precision polarimetry = dI/I ~ 10⁻⁴ in 10 sec in IR
- Infinite isoplanatic angle
 - \rightarrow Large field of view = 200" x 200"
- Accessibility to shorter wavelength
 - → Include Mg II 280nm (TBD)
- Continuous sun light 24h/day
 - \rightarrow S/C orbit design

1.5m class aperture

Sensitivity to magnetic field



Courtesy of chrom. diagnostic sub-WG (2009~2010)

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1.5mφ, nominal throughput, Zeeman effect,0.1"x0.1" pix, 1sec integration

He I 10830Å



 In order to observe the LP by the Hanle effect, the minimum requirement of the sensitivity is 2-3x10⁻⁴. The goal is 1x10⁻⁴.

High spatial resolution vs. high polarimetric sensitvity

Contradicting each other

 \rightarrow Need multi-instruments (modes)

Telescope assmebly: collect photons spatial resolution image stabilization modulate polarization states Focal plane instruments: resolve spectral information

analyze polarization states spatial sampling (high res, high polarimetric)

Candidate spectrum lines for SUVIT

Instrument	Spectrum line	n line wavelength Purpose	
Vis/UV broadband imager	continuum	TBD	High res. Img of photospehre
	(Mg II h/k	280nm)	High res img of chromosphere
	CN band	388nm	Granules and magnetic elements
	Ca II H	396nm	High res img of chromosphere
	G-band	430nm	Granules and magnetic elements
Vis/NIR narrowband imager	owband imager Mg Ib2 512nm		Low chromosphere V and B
	Fe I	525nm	Photosphere B
	Na ID1 (D2)	589nm	Low chromosphere V and B High photosphere
	Ηα	656nm	High chromosphere V
	Ca II IRT	854nm	High chromosphere T, V and B
	(He I	1083nm)	High chromosphere V and B
UV/Vis/NIR spectrometer	(Mg II h/k	280nm)	High chromosphere T and V
	Fel	525nm	Photosphere B
	Ca II IRT	854nm	High chromosphere T, V and B
	Hel	1083nm	High chromosphere V and B

Sever Contamination Control Necessary

Mg II h&k: waiting for IRIS results

need dedicated Instrumentation and tests are difficult request much sever contamination control than Hinode case



We do not understand exactly the cause of degradation of SOT throughtput.

→ Need further experiments for Solar-C!





Coating



Optical layout in the spectrograph package



Reimaging lens Focus adjusting mechanism

1500 mm

Slit-IFU Coexistence Design



Fiber IFU in progress



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input array

- Fiber ribbon developed by Collimated Holes (Inc., CHI) with H. Lin (Hawaii Univ.)
- Size of the elemental fiber 10µm x 40µm.
- Material: Bolosilicate Glass
- Polarization maintaining (to be verified)





output array

Slit scan is too slow to capture the chromospheric dynamics → Slit + IFU(Image slicer) spectro-polarimetory



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Strawman design of the broadband filtergraph

- Obtain a monochromatic image of the solar photosphere and chromosphere using interference filters at the best possible spatial and temporal resolution.
- The resolution of 0.05" is achieved at the shortest wavelength (~280 nm) with the high resolution mode.
- The wide FOV mode is also considered to have the FOV consistent with SP.

Entrance pupil	$60 \text{ mm} \rightarrow 56.4 \text{mm}$	
Detector size	4096 x 4096, 12µm/pixel	
High-resolution mode		
Focal length	6600 mm (F/110)	
Pixel scale	0.015" /pixel	
FOV	61" x 61"	
Wide-FOV mode		
Focal length	2200 mm (F/36.7)	
Pixel scale	0.045" /pixel	
FOV	184" x 184" (matching with the SP FOV)	

Pass-bands	279 nm	380 nm	393 nm	TBD
Spectrum lines	Mg II k/h	CN band	Ca II K	contin.



Strawman design of the narrowband filtergraph

- Perform imaging-spectroscopic (+polarimetric) observations at chromospheric and photospheric lines.
- The current baseline is to employ a LC Lyot filter as tunable filter.
- The FOV coverage is limited by the available aperture size of TF.

	Entrance pupil	$60 \text{ mm} \rightarrow 56.4 \text{mm}$	
	Telecentric beam @ TF	~F/40 (in the case of a Lyot filter)	
	TF band width	~100 mÅ	
Q	Detector size	4096 x 4096, 12μm/pixel	
	Focal length	2475 mm (F/41)	
,	Pixel scale	0.04" /pixel	
ני	FOV	~ 100" x 100" (limited by the aperture size of TF)	

	Pass-bands	517 nm	525 nm	589 nm	656 nm	854 nm
1	Spectrum lines	MgIb	Fe I	Na I D1	HΙα	Ca II
F.						1083nm

Hel





To expand FOV: Either 2D mosaic scan or small pupil sub-channel

EUVST

- It will provide the crucial link between the photospheric and chromospheric magnetic field and plasma characteristics obtained by the SUVIT and the high temporal and spatial resolution images of the corona provided by the XIT.
- Key science requirements
 - Simultaneous spectroscopic measurements in emission lines sampling all temperature regions present in the solar atmosphere, i.e., Chromosphere – TR – Corona - Flare
 - Resolving 0.3" spatial scale to validate the structure connections among all temperature regions
 - Effective area an order of magnitude higher than currently available for solar studies, much improving temporal cadence.
- As major European contribution to Solar-C, this telescope with naming LEMUR (Large European Module for Solar Ultraviolet Research) has been proposed to ESA as a mission of opportunity in the 2010 Cosmic Vision Call.

EUVST(LEMUR): instrument requirements & layout

- Optics: single off-axis mirror ۲ $(30 \text{ cm}\phi, \text{ f}=360 \text{ cm})$ and a grating
- Telescope length: 430cm

Field	Required value
Spatial resolution	<0.28"
Spectral resolution	$\overline{\lambda}$ / $\Delta\lambda$ 17 000 to 32 000
Doppler shift accuracy	$\leq 2 \text{ km s}^{-1}$
Doppler width accuracy	\leq 5 km s ⁻¹
Temperature coverage	0.01 to 20 MK
Field-of-view	slit length 280″
raster coverage	300" (w/o re-pointing)
Exposure times	$\leq 10 \text{ s} (0.28'' \text{ sampling})$
	$\leq 1 \text{ s} (1'' \text{ sampling})$
Mirror micro-roughness	about 3 Å rms or better

Mirror micro-roughness



With low scattering optics, for exploring low EM regions (MR and CH).

EUVST/LEMUR

Item	Description
Telescope	Off-axis single mirror telescope: diameter of primary: 30 cm
Focal Plane Instruments	Spectrographs, Slit imaging camera for co-alignment
Wavelength coverage	Spectrographs: First order: 17–21 nm, 69 – 85 nm, 92.5 – 108.5 nm, 111.5–127.5 nm Second order: 46–54 nm, 56–64 nm Slit imaging camera: A chromospheric line/band (e.g., continuum around 160 nm)
Temperature coverage	0.01 - 20 MK
Imaging performance	0.28" in 80% encircled energy over nominal field of view (FOV) (0.14" reachable in the 17-21 range on a reduced FOV)
Spatial sampling	0.14" at detector
Slit	0.14", 0.28", 0.56", 1", 5"
Spectral resolution $(\lambda/\Delta\lambda)$	17,000~30,000
Exposure time	1-5 s for 0.28 arcsec sampling $0.1-0.5$ s for 1 arcsec sampling
Field of view	280 arcsec (along slit) × 300 arcsec (scanning direction)

Temperature coverage and radiometric performances



Flare lines: Fe XVIII 974 Fe XIX 592 Fe XX 721 Fe XXI 786 Fe XXIII 1079 Fe XXIV 192

• Broad temperature coverage 10^4 K to 10^7 K

 Performance at two temperature regions important for coronal heating studies

XIT

- X-ray Imaging (Spectroscopic) Telescope for Solar-C
 - Expected contributions from imaging observations of the corona
 - Reveal forms and mechanisms of (storage and) dissipation of energy
 - Quantitative understanding on the reconnection physics
 - Connectivity with the lower atmosphere
- Two possibilities under study for the X-ray telescope
 - − (1) Ultra-high-resolution normal incidence EUV telescope
 → Context information for LEMUR
 - (2) Photon-counting imaging-spectroscopic grazing incidence X-ray telescope

Preliminary Illustration of Solar-C X/EUV Telescope "Everything in a package"



NORMAL INCIDENCE / GRAZING INCIDENCE HARD AND SOFT X-RAY

Preliminary Features of Ultra-High-Resolution EUV Telescope

Item EUV Telescope		EUVS/LEMUR
Telescope	32cmφ primary mirror 3 sector coating (Ritchey-Chretien; ~4 m length) Tip-tilt control of the secondary	Image - Lower TR - Lower corona - Hot corona (with 1 MK)
Wavelength channel Temperature coverage	171 Å, 94 Å, and 304 Å or UV band (0.8MK / 1MK & 8MK(FL) / 0.05 MK) [some from 94/171/195/211/304/335Å]	Provide context for EUVST
Spatial resolution	0.2" – 0.3" (0.1" pixel)	0.16" pixel
Exposure cadence	Exposure time : AR (<3 MK) – 1 s, FL – 0.1 s Cadence : < 10 s (for AR <3 MK)	Exposure time : AR – 1-5 s (w/ 0.33" spatial sampling)
Field of view ~400" x 400"		200" nominal > 300" extended

Pointing Stability, Control of Micro-Vibration

Request image stabilization system for all telescopes



SOLAR-C Status



Need Strong International Collaboration

Japan:

launcher

bus system

SUVIT-TA

SUVIT-SP (except for IR camera)

International partners:

(SUVIT-TA M1&M2 mirrors) SUVIT-FG, (correlation tracker) SUVIT-SP IR camera EUVST XIT

others

Synergy with other space and ground-based instruments

10 years later, SOLAR-C would be a unique space-borne solar observing instrument

SOLAR-C high-resolution mag, chromosphere, and corona However, spectral

lines are limited.



Multi-line observation, and coronal magnetic field observation are helpful to much enhance the science

NST GREGOR NLST ATST EST



Thank you for your attention

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