NGSPM-SOT Report

July 2017

Next Generation Solar Physics Mission
Science Objectives Team
(NGSPM-SOT)

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Executive Summary

In June 2016, the United States National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA), and European Space Agency (ESA) chartered a Next Generation Solar Physics Mission (NGSPM) Science Objectives Team (SOT) to study and report on a multilateral solar physics mission concept. The SOT was formed as a means of improving international coordination in solar physics, and in particular developing an NGSPM concept for the next decade. This is likely to be realized as a Japan-led mission launched after 2024, with substantial contributions from the United States and Europe. The primary role of the SOT was to develop and document **scientific objectives and priorities** for an NGSPM, within the resources and framework specified by the agencies. The guiding philosophy was that a next-generation effort should bring closure to science objectives by exploring and exploiting new windows on, e.g., wavelength, continuity, spatial resolution, temporal resolution, spectroscopy and polarimetry, vantage point and orbit, with due consideration given to readiness of technology and analysis methods.

The Charter of the SOT stated that the team was intended to “represent the broad interests of the heliophysics research community”. SOT members conducted more than 6 sessions at scientific meetings in the US, UK and Japan to inform the community of our work and receive feedback. A public call for white papers in the fall of 2016 resulted in 34 submissions describing science objectives, instruments and/or mission concepts, covering a wide variety of topics. The most common topics involve coronal heating, magnetic geometry/topology/ reconnection and heating processes in flares and CMEs. Most of the measurements requested fall into three categories, spectroscopic, magnetic or multi-platform observations.

Drawing on the science objectives of the white papers, the 2015 Solar-C proposal, and discussions within the SOT, the following set of top-level science objectives was adopted.

- Formation mechanisms of the hot and dynamic outer solar atmosphere
- Mechanisms of large-scale solar eruptions and foundations for predictions
- Mechanisms driving the solar cycle and irradiance variation

SOT members wrote specific sub-objectives (17 in total) under these headings and listed the essential observational tasks (56 in total) and measurements required to address each of them. That list of required measurements implied a set of notional instruments (15 in total) to satisfy all, and some critical specifications for those were compiled (spatial and temporal resolution, field-of-view, possible wavelength range). Lengthy discussions took place evaluating the scientific sub-objectives according to criteria such as impact to solar physics, need for space observations, and technical feasibility (see Section 3.1 for the complete list of criteria). This “bottoms-up” review of the current state of heliophysics showed that there are two broad avenues, both with distinct merits, for future research: physical mechanisms on elemental (small) scales, versus global processes affecting/involving large fractions of the solar interior and/or atmosphere. Transformative progress would certainly be made possible by sustained, global views from multiple view points, as is discussed in Section 3.3.1. This provides a strong motivation for international coordination over the upcoming decades to fill critical gaps in vantage points in order to obtain a truly global understanding of the Sun. However, comprehensive implementation schemes likely exceed the resources available for a NGSPM on the timescale of the next decade. Therefore, the SOT chose to focus its recommendations on the other avenue, i.e., **the study of fundamental physical processes at high spatial and temporal resolution through all temperature regimes of the solar atmosphere**.

There is every reason to believe that a high-resolution focus for NGSPM will be rich scientifically. Game-changing discoveries may be found on these elemental scales, such as the nature of magnetic stresses resulting from braiding of magnetic field lines; the magnetic topology at the footpoints of spicules, jets, and prominences; the transport of energy via Alfvén waves in flares; and the development and effects of turbulence in all levels of the solar atmosphere. Given current constraints, probing the Sun at highest resolution is both feasible and well-suited to NGSPM near-term opportunities. It will be important for NGSPM to observe in conjunction with ground-based observatories, in particular DKIST (and later EST) in order to combine the unique strengths of space- and ground-based resources.

Considering a minimum set of instruments with which NGSPM can address the greatest number of high-priority Tasks consistent with the objective of small length- and time-scale activity, we find that a majority of the key required measurements can be met with the following suite of instruments:

1. 0.3" coronal/TR spectrograph
2. 0.2"- 0.6" coronal imager
3. 0.1"- 0.3" chromospheric/photospheric magnetograph/spectrograph

While other combinations of candidate instruments would likely also produce significant results, the list above represents the smallest set of instruments addressing as many as 32 of the 56 essential observational Tasks listed in Section 3.1; it is the list of instruments that the SOT feels should receive the highest priority for selection. The great majority of the Tasks require some combination of instrumentation for closure or significant progress. Thus the strawman suite of instruments considered above has been optimized to maximize the scientific return from the NGSPM.

The Charter of the NGSPM-SOT assigns the task of suggesting possible mission profiles that could satisfy the science objectives identified by the SOT, within the likely available resources. The three instruments outlined above could be realized in one single large mission. This large mission is smaller, less complex, and less expensive than the Solar-C proposed in 2015. The largest telescope has decreased in size, its focal plane package is less complex, and the launch cost has been reduced significantly. The second mission concept is to form a constellation of small or middle-class satellites for realizing the three instruments, by utilizing spacecraft of JAXA, NASA, and/or ESA (including ESA member states). The merit of this mission concept is to increase the possibility that some of the instruments are launched as early as possible in the mid-2020's, but a risk is that the scientific synergy among the three instruments will be limited unless there is significant overlap in observing time of the missions.

The SOT finds that **the suite of instruments listed above are the highest priority for advancing the science objectives mentioned above within the next decade**. We recommend that **the NGSPM consist of the instruments listed above operating simultaneously, in full-Sun orbit(s), with sufficient telemetry coverage**.

We recommend that **NGSPM be realized with a single platform, as a JAXA Strategic Large mission with contributions from NASA (SMEX-level), ESA (MoO), and ESA member**

states. **If the single-platform approach is not possible or available, a combination of two or three spacecraft can achieve many of the NGSPM objectives, with some loss of capability and at increased risk.**

We recommend that **the agencies form a unified Science Definition Team for NGSPM as soon as possible to define the agencies' respective contributions in more detail.**

Some more specific recommendations to the three agencies are also included, in the complete list in Section 4.8.

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Acronyms

AGU	American Geophysical Union
AIA	Atmospheric Imaging Assembly
AO	Announcement of Opportunity
AR	active region
ASJ	Astronomical Society of Japan
AU	Astronomical Unit
CH	coronal hole
CLASP	Chromospheric Lyman-Alpha Spectro Polarimeter
CME	Coronal Mass Ejection
CMOS	Complementary MOS (image sensor)
CSHKP	Carmichael-Sturrock-Hirayama-Kopp-Pneuman
CZ	convection zone
DKIST	Daniel K. Inouye Solar Telescope
EIS	Extreme UV Imaging Spectrometer
ENA	energetic neutral atom
EPIC	European Participation in Solar-C
ESA	European Space Agency
EST	European Solar Telescope
EUV	Extreme ultra violet
EW	east-west
FIP	first ionization potential
FOV	field of view
FOXSI	Focusing Optics X-ray Solar Imager
FWHM	full width at half maximum
GBO	Ground-based Observatories
GOES	Geostationary Operational Environmental Satellite
Hi-C	High Resolution Coronal Imager
HMI	Helioseismic and Magnetic Imager
HSO	Heliophysics System Observatory
HXR	Hard X-ray
ID	identification
IRIS	Interface Region Imaging Spectrograph
ISAS	Institute of Space and Astronautical Science
JAXA	Japan Aerospace Exploration Agency
JSPC	Japan Solar Physics Community
KE	kinetic energy
MDI	Michelson Doppler Imager
MHD	Magnetohydrodynamics
MIDEX	Medium-Class Explorers
MK	Million Kelvin
MoO	Missions of Opportunity
Mx	Maxwell
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
NEO	near earth orbit
NGSPM	Next Generation Solar Physics Mission
NIR	Near Infrared

NLFFF	nonlinear force-free field
NS	north-south
NST	New Solar Telescope
NUV	Near ultra violet
PIL	polarity inversion line
PROBA	Project for On-Board Autonomy
PSP	Parker Solar Probe
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
Q&A	Question & Answer
QS	quiet Sun
SAD	Supra-arcade downflow
SDO	Solar Dynamics Observatory
SMEX	Small Explorers
SO	Solar Orbiter
SOHO	Solar and Heliospheric Observatory
SOT	Science Objectives Team (of NGSPM)
SOT	Solar Optical Telescope (on Hinode)
SSI	Solar Spectral Irradiance
SST	Swedish Solar Telescope
SUMER	Solar Ultraviolet Measurements of Emitted Radiation
SUVI	Solar Ultraviolet Imager
SWAP	Sun Watcher using Active Pixel System Detector and Image Processing
SXI	Solar X-ray Imager
SXR	soft X-ray
SXT	Soft X-ray Telescope
TES	Transition Edge Sensor
TR	transition region
TRACE	Transition Region and Coronal Explorer
TSI	Total Solar Irradiance
UK	United Kingdom
US	United States (of America)
UV	Ultra violet
WG	Working Group
XRT	X-Ray Telescope

Chapter One: Introduction

In June 2016, the United States National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA), and European Space Agency (ESA) chartered a Next Generation Solar Physics Mission (NGSPM) Science Objectives Team (SOT) to study and report on a multilateral solar physics mission concept (**Appendix A**). This effort builds upon the highly successful collaborations between NASA, JAXA, and ESA, including Yohkoh (Solar-A), Hinode (Solar-B), Geotail, Chromospheric Lyman-Alpha Spectro Polarimeter (CLASP) (sounding rocket), and the Solar and Heliospheric Observatory (SOHO).

The SOT was formed as a means of improving international coordination in solar physics, and in particular developing an NGSPM concept for the next decade. This is likely to be realized as a Japan-led mission launched after 2024, with substantial contributions from the United States and Europe (subject to the normal proposal and peer review cycles of all the partners). The SOT was encouraged by the agencies to consider mission design options on different scales to be ready for future opportunities should they arise.

The primary role of the SOT was to develop and document scientific objectives and priorities for an NGSPM, within the resources and framework specified by the agencies. **Appendix B** describes these science objectives, and the outstanding tasks and key observations required to achieve them. Changes in landscape due to major new capabilities offered by, e.g., the Daniel K. Inouye Solar Telescope (DKIST) were part of our considerations. Prioritization thus emphasized science enabled by space observations and not accessible to existing or near-term assets, either space or ground-based (see **Appendix C**). The guiding philosophy was that a next-generation effort should bring closure to science objectives by exploring and exploiting new windows on, e.g., wavelength, continuity, seeing/resolution, vantage point and orbit, with due consideration given to readiness of technology and analysis methods.

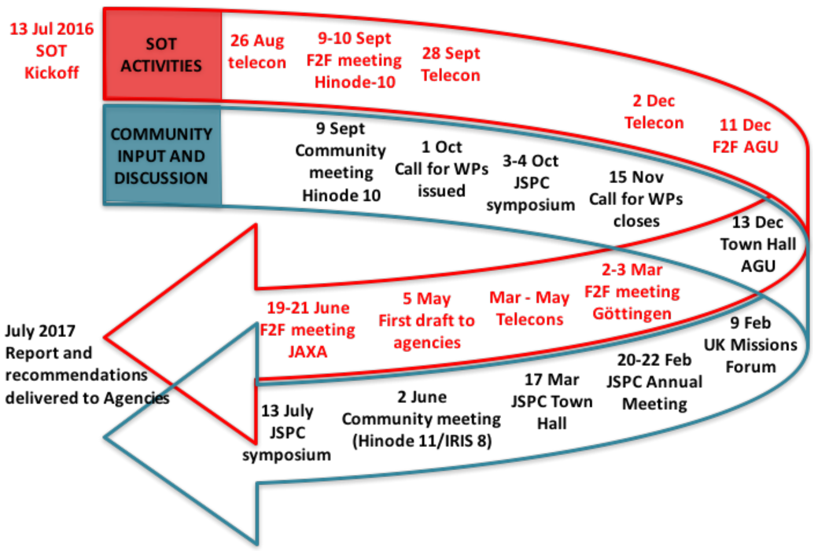


Figure 1-1: SOT activities and community input

The membership of the SOT was selected jointly by the Institute of Space and Astronautical Science (ISAS)/JAXA, NASA, and ESA, and included four members from Japan, four from the US and four from ESA member states. Two helioseismology experts were added later to the membership for assessing helioseismology-related objectives. The SOT membership was chosen to represent the full range of solar physics sub-disciplines (**Appendix D**). SOT members acted as points of contact with the worldwide community, from whom input was sought in the form of short 'white papers'. These served two main purposes; to widen the scope of the discussion beyond the expertise and interest of the SOT members, and -- grouped roughly by objective/type of observation/platform -- to generate a top level view of the momentum behind different ideas, the level of community interest and backing, and the level of technological readiness. The team met regularly over the course of a year, with several telecons and 4 face-to-face meetings. In addition to the white papers, community input was sought by organizing town-hall or discussion sessions at 8 meetings in Japan, the US and the UK. The timeline for SOT activities and community input is shown in Figure 1-1.

The report is structured as follows, with the intention of closely following the charter given to the SOT by the agency partners (see **Appendix A**). In Chapter 2 we give details of the input gathered by the SOT from the community. In Chapter 3 we present prioritized scientific objectives and their required measurements, taking into consideration alignment with agency goals and likely resources. In Chapter 4 we present a set of recommended mission design strategies, and discuss international coordination necessary to realize the NGSPM.

Chapter Two: Community Input

2.1. Town Hall meetings

The Charter of the SOT makes plain that the Team is intended to "represent the broad interests of the heliophysics research community". The Team thus felt a strong obligation to take input from the community to ensure that our discussions were not too narrowly focused, and to provide information back to the community regarding our progress and methodology. To this end, we conducted Question & Answer (Q&A) sessions at major conferences to interact with attendees. In parallel, the membership list of the SOT was published so that community members could freely communicate with us informally at any time. In the following paragraphs, we briefly summarize these Q&A sessions; more detailed descriptions are given in **Appendix E**.

2.1.1 Q&A at Hinode-10

The first "Town Hall"-type meeting was conducted during the Solar-C session at the Hinode-10 meeting in Nagoya, Japan, primarily for the purpose of introducing the SOT to the community and starting a dialogue. After presentations of the SOT charter and some preliminary studies of instrument concepts in Japan, an extensive Q&A with the full audience was conducted, addressing the goals and objectives of the SOT and the NGSPM.

2.1.2 Town Hall at AGU

The second major Q&A session was a Town Hall meeting at the AGU in San Francisco. Being in December, this occurred approximately half-way through the SOT's deliberations. The SOT members were joined by agency representatives from NASA and JAXA, who presented the rationale for chartering the SOT. The reports were followed by an extensive Q&A, including discussion about the agencies' expected budget, timeframe, and mission scope (small/medium/large).

2.1.3 UK Community Meeting

During the UK Solar Physics Community's annual missions forum, attended by around 50 community members, the purpose, membership and progress of the SOT were described, based on the presentations given at the AGU Town Hall. The outcome of the call for white papers was also summarised.

2.1.4 Japanese Community Meetings

Community meetings were organized multiple times by JSPC (Japan Solar Physics Community) to discuss science objectives and future directions of solar physics in Japan. The first symposium (3-4 October 2016, ISAS/JAXA) was an opportunity to discuss key science objectives based on the NGSPM-SOT study at the early phase with the community. Four sub-groups formed in the JAXA Solar-C WG presented science objectives and mission concepts based on Epsilon opportunity and identified scientific issues to be addressed in the next meeting, which was the JSPC annual meeting on 20-22 February 2017 at ISAS/JAXA. Then, some schedule updates on the announcement of opportunity in JAXA were reported to the community during the ASJ (Astronomical Society of Japan) meeting (Fukuoka) on 17 March

2017. The JSPC also held a one-day meeting on 13 July 2017 at NAOJ for having community consensus toward the coming Epsilon AO, with inputs from NGSPM-SOT report as well as study updates from the JAXA Solar-C WG.

2.1.5 Q&A at Hinode-11

At the conclusion of the Hinode/IRIS joint science meeting in May-June 2017, in Seattle, Washington, a 75-minute session was allocated for a presentation and Q&A regarding the Draft Report of the NGSPM-SOT. Following a PowerPoint presentation of the main points of the Draft Report, a Q&A with the audience discussed initial reactions of the community to the findings and preliminary recommendations.

2.2. White papers

2.2.1. Science objectives

Table 2-1 (at the end of this Chapter) provides a brief summary (the lead author, title, primary science theme, closest sub-objectives, and instrument discussed) of all the 34 white papers received. The 34 papers in total cover a large variety of science objectives and ideas. Table 2-2 shows the number of white papers categorized according to science theme. This table shows that coronal heating, magnetic geometry/topology, and heating in flares and CMEs remain very high priority topics for large fractions of the scientific community. Coronal heating is one of the fundamental questions in solar and stellar physics, and many solar physicists consider spectroscopic and magnetic-field (spectro-polarimetric) observations at higher resolution and higher accuracy to be of utmost importance. Magnetic geometry and topology are fundamental to understanding the formation mechanism of the hot and dynamic outer atmosphere. There is also a sense that our knowledge of heating processes involved in flares and CMEs is incomplete.

Table 2-2: Ranked topics based on the submitted white papers

#	Topics	# of WPs	Related sub-objectives
1	Coronal Heating	15	I-1, I-2, I-3, I-4, I-5
2	Magnetic geometry/topology/reconnection	11	I-1, I-4, I-5, I-6, II-1, II-2, II-4, II-5
3	Heating processes in flares/CMEs	9	II-3, II-4, II-6
4	Magnetic energy buildup and instabilities leading to eruptions	5	I-6, II-1, II-2, II-5
5	Probing flare processes via particle acceleration	7	II-4, II-6
6	Solar dynamo and magnetic dynamics	6	II-5, III-2, III-3
7	Solar wind acceleration	6	I-5
8	Solar internal structure	4	III-1, III-2
9	Space weather monitoring	5	II-1, II-2, II-3
10	Irradiance	3	III-4

Some white papers discuss the importance of other aspects of solar flares, e.g., magnetic energy buildup and instabilities leading to eruptions, and particle acceleration processes. The causes of long-term variations of solar magnetic activity are particularly poorly understood, requiring considerable progress in understanding the workings of the solar dynamo. For this task, observations relating to the solar dynamo and probing internal structure may give unique constraints on theory and models; we received eight white papers on these topics. Three white papers discussed total and solar irradiance variability, in particular as a function of solar latitude. There were also six white papers that addressed science associated with solar wind acceleration.

Having these white papers was valuable to make sure that no topics of interest to the broader community were missed in our team's discussions (Chapter 3).

2.2.2. Instrument concepts

The proposed concepts of observations are classified in a) spectroscopic observations (Figure 2-1), b) magnetic-field observations (Figure 2-2), and c) multi-platform observations (Figure 2-3). Note that a few white papers that cannot be classified in these three categories are shown in a) spectroscopic observations (in particular, in-situ observations). In Chapter 3, science objectives of NGSPM will be classified into three categories:

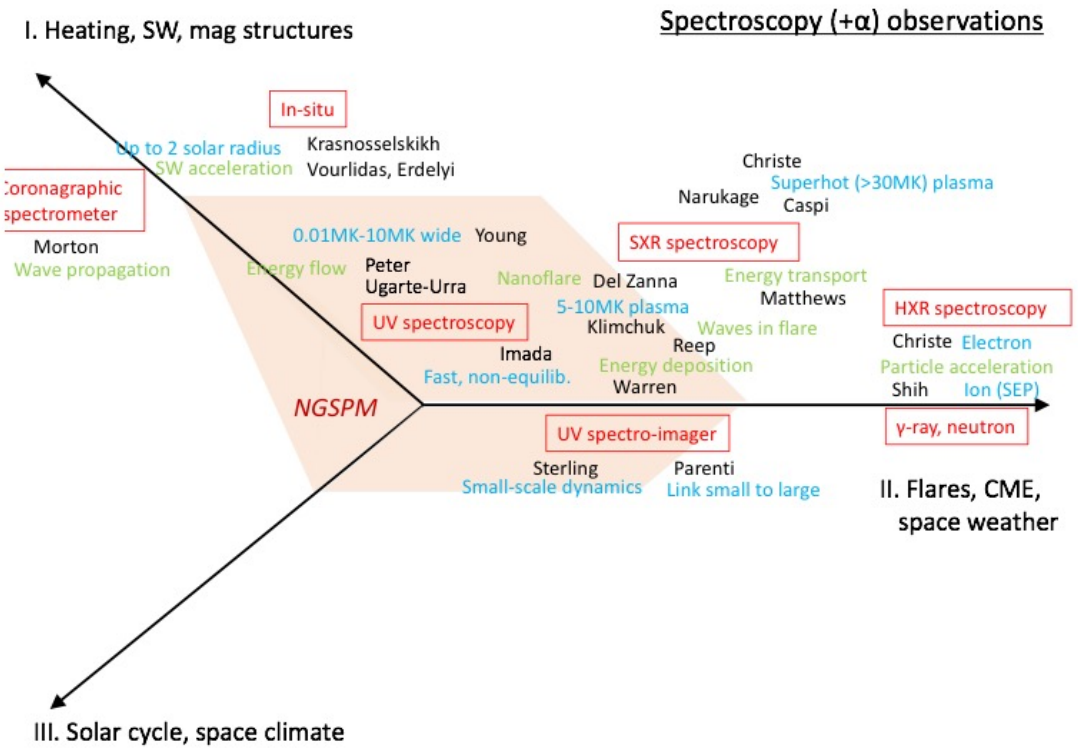
I. Formation mechanisms of the hot and dynamic outer atmosphere;
II. Mechanisms of large-scale solar eruptions and foundations for predictions;
III. Mechanisms driving the solar cycle and irradiance variation.

The upper panel of Figures 2-1, 2-2, and 2-3 represent a 3D map defined by the three science objectives, in which is given the instrument concept (type of instrument, key performance, and scientific target) proposed by each white paper for addressing its primary science objective. The area covered by the instruments proposed for NGSPM (in Chapter 3 below) is shown by a hatched region around the origin. The lower panels in Figures 2-1 and 2-2 give instrument concepts of the white papers as a function of wavelength in the horizontal axis and atmospheric height (plasma temperature) in the vertical axis.

a) Spectroscopic observations

Eight white papers (Young, Peter, Ugarte-Urra, Imada, Klimchuk, Del Zanna, Warren, Reep) proposed a high-throughput EUV spectroscopy instrument, although the key performance stressed in each paper is different, including a wide temperature (0.01K-10MK) coverage for tracing energy flow (Young) and for magnetic connectivity of the atmosphere (Peter), high cadence for dynamic diagnostics in loop structures (Ugarte-Urra) and for diagnosing non-equilibrium plasma (Imada), high temperature (5-10MK) lines for investigating nanoflares (Klimchuk, Del Zanna), and energy deposition and waves in flares (Warren, Reep). For nanoflare investigations, some white papers discuss the importance of line selection (Del Zanna, Klimchuk) and also propose spectroscopy in soft X-ray and low-energy hard X-ray ranges (Narukage, Christe, Caspi). New technologies are proposed for soft X-ray spectroscopy, i.e., photon-counting with high speed readout CMOS detectors (Narukage), and TES X-ray microcalorimeter arrays (Christe). Low-cost and low-resource instruments that have already been flown on sounding rockets and CubeSats are also proposed (Caspi). Soft X-ray spectroscopy is proposed for diagnosing superhot (>30 MK) plasma, and for investigating non-thermal distributions and energy transport in flare plasma (Matthews). Proposals were also made to investigate particle acceleration in flares by hard X-ray spectroscopy for electrons (Christe, Reep, Warren) and by gamma-ray and neutron monitoring for ions (Shih).

UV imagers for spectral lines are suggested with super-high spatial resolution for topological studies of small-scale dynamics (Matthews, Sterling), and with a moderate spatial resolution for linking small-scale dynamics to large-scale magnetic structures (Parenti).



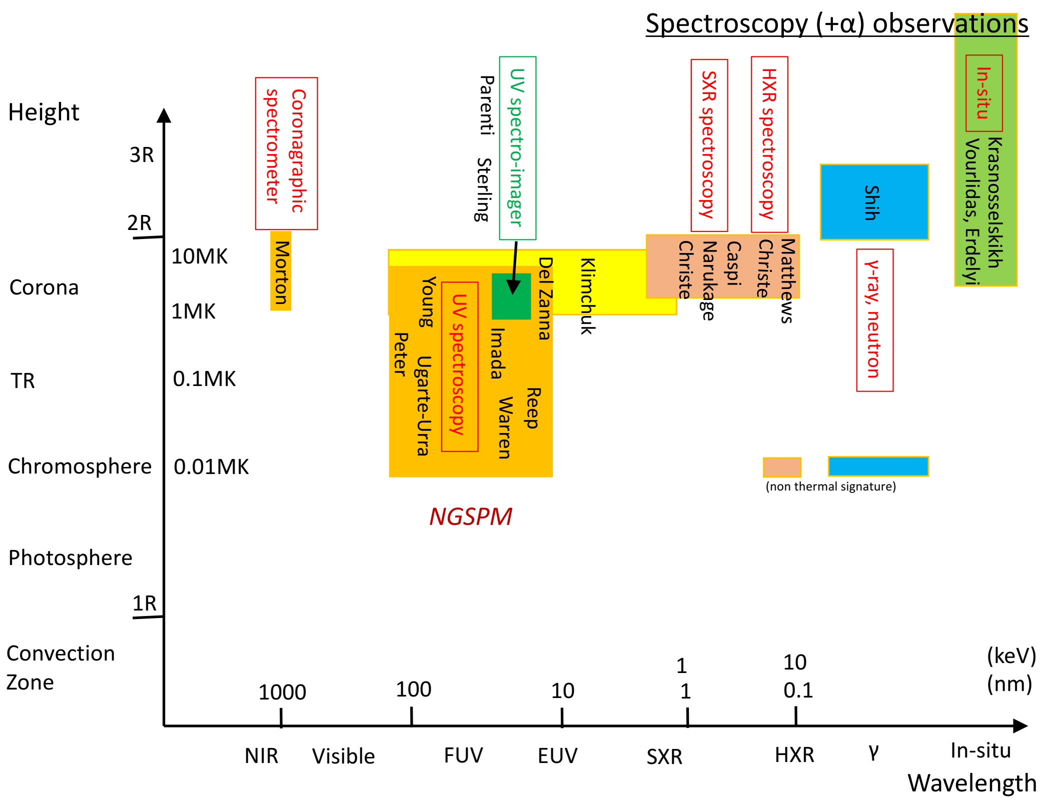


Figure 2-1: Mapping of white papers for spectroscopic observations (upper) in three science objective categories and (lower) in wavelength and atmospheric height

Investigations from the chromosphere through the outer corona and into the heliosphere may be important for understanding the acceleration of the solar wind. White papers exploring solar wind origins argue for Doppler velocity measurements covering coronal hole boundaries as well as active regions (Parenti), instruments capable of measuring polarization in hard X-ray sources (Berrilli), and imaging-spectrometer coronagraph for tracing waves propagating up to 2 solar radii (Morton). Others suggest *in situ* measurements by missions approaching very close to the solar surface (Krasnosselskikh), at high latitudes (Vourlidas), or as part of a comprehensive solar observatory at L1 (Erdelyi).

b) Magnetic field observations

Optical telescopes with a variety of aperture sizes, all aiming at measuring the magnetic field, were proposed, including 50cm-class visible-light/NIR telescopes for diagnosing chromospheric magnetic fields relating to flares (Ichimoto) and high-cadence, long-duration observations of target regions in the photosphere and chromosphere (Berrilli), a 1m-class visible-light/NIR telescope for investigating magnetic structures of sunspots above and below the visible surface (Zhao), and a 3m-class ultra-high resolution telescope covering wavelengths from UV to NIR for studying magneto-convection and dynamo processes (Collet). 50-cm optical telescopes with imaging spectropolarimeters (Orozco) and a Visible/IR coronagraph with spectropolarimeter (DeLuca) were also proposed to target prominence/filament magnetic structure and evolution. Optical magnetographs with Doppler velocity measurement capabilities were also a standard requirements on all the dynamo-oriented white papers (Appourchaux, Vourlidas, Judge, Erdelyi).

New capabilities for directly measuring the magnetic fields in the upper atmosphere beyond the chromosphere have also been proposed. This was outlined in 2 white papers by expanding spectro-polarimetry in the UV (Ishikawa, Casini) from the upper chromosphere to the lower transition region. Furthermore, spectro-polarimetry with a coronagraph (Lin) is described as a pathfinder for tomographic measurements of the coronal magnetic field.

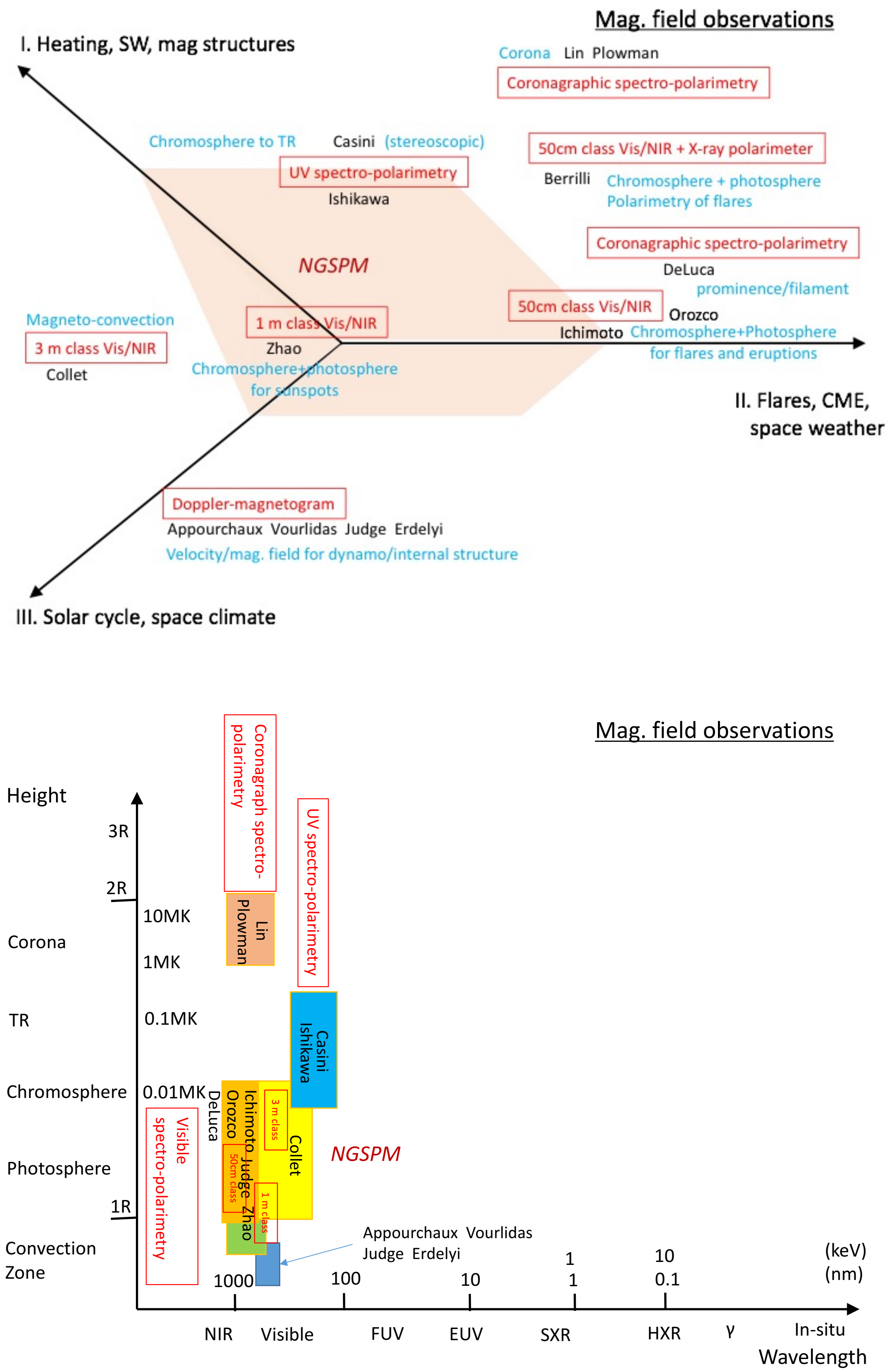


Figure 2-2: Mapping of white papers for magnetic field observations (upper) in three science objective categories and (lower) in wavelength and atmospheric height

c) Multi-platform observations

An alternative to a single-platform observatory-type mission is proposed (De Luca), in which NASA, ESA, and JAXA each define a small or mid-class mission and the set of three small missions forms a solar observatory on orbit. Proposals for stereoscopic measurements obtained by complementing a NEO 50cm-class telescope with another 50cm telescope located far from the Earth (e.g. L5) were made (Orozco, Judge). The idea is to improve magnetic field measurements and monitoring of the magnetic field at the chromosphere and photosphere for developing space weather forecast capabilities. Finally, a dual spacecraft mission is proposed (Krasnosselskikh) where one spacecraft carrying in situ instruments goes very close to the sun, as it is monitored by a second spacecraft carrying remote-sensing instruments at a significantly-higher orbit.

Missions leaving Earth orbit may be important for obtaining new understanding of the Sun from different vantage points. The Lagrangian point L1 provides a stable environment in which a large formation flying mission is proposed for achieving ultra-high resolution observations (Erdelyi). Missions on out-of-ecliptic orbits have been advanced for polar investigations (Appourchaux, Vourlidas), while a spacecraft at the Lagrangian point L5 has been described, whose aim is to provide the synoptic observations needed to determine the 3D structures of coronal mass ejections (Plowman). Multi-vantage-point, multi-mission observations of the Sun (Brun) capture a global view of the Sun in all longitudes and latitudes for understanding the global dynamical state of solar magnetism.

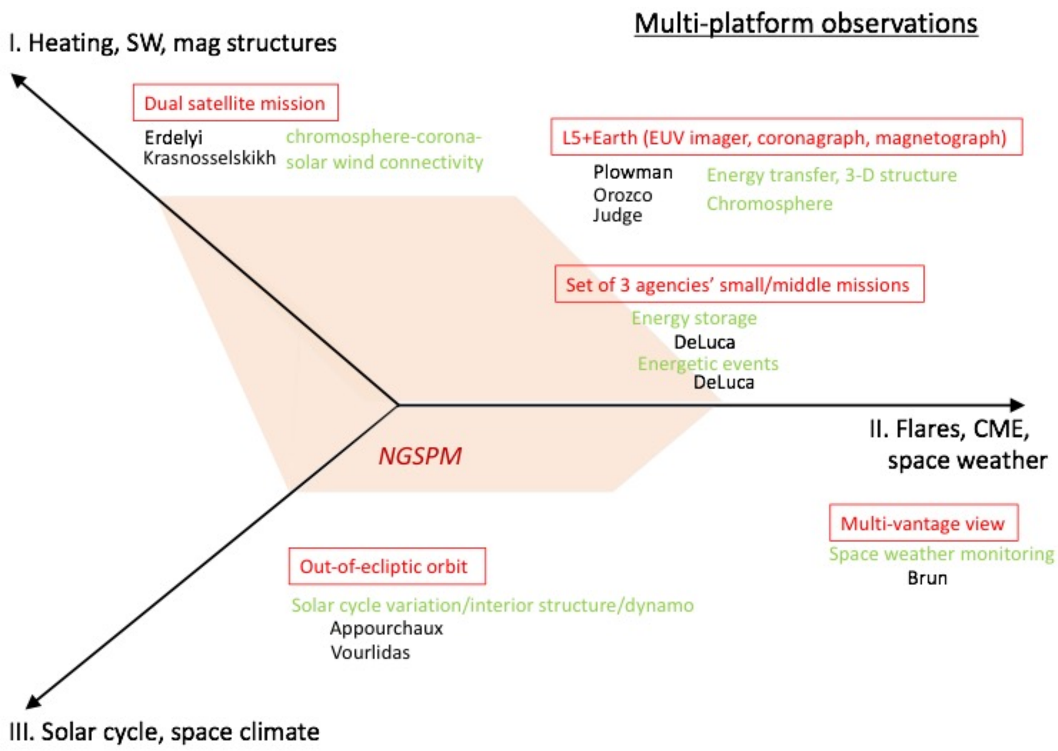


Figure 2-3: Mapping of white papers for multi-platform observations in three science objective categories

Table 2-1: List of white papers

#	Lead author	Title	Science Theme	Closest sub-objective	Instrument Category
1	Ugarte-Urra	Science Objective: Understanding Coronal Loop Plasma Dynamics with 2D time-resolved spectroscopy	Coronal heating	I-1, I-2, I-3, I-4, I-5	(E)UV spectroscopy, spatially resolved
2	Caspi	Diagnosing Coronal Heating Processes with Spectrally Resolved Soft X-ray Measurements	Coronal heating	I-2, I-5, II-6	X-ray spectroscopy, spatially resolved (soft)
3	Young	Energy Transfer from the Chromosphere to the Corona Using Oxygen as a Trace Element	Coronal heating	I-1, I-3	(E)UV and X-ray spectroscopy, spatially resolved; UV and EUV imaging for context; high-resolution magnetic measurements.
4	Imada	Clarify the Energy Transfer from the Photosphere to the Corona and Diagnose the Energy Dissipation Region: UV/EUV High-Throughput Spectroscopic Telescope	Coronal heating; Heating processes in flares/CMEs	I-2, II-4	(E)UV spectroscopy, spatially resolved
5	Klimchuk	The Case for Spectroscopic Observations of Very Hot (5-10 MK) Plasma	Coronal heating; Heating processes in flares/CMEs	II-4	(E)UV and X-ray spectroscopy, spatially resolved
6	Del Zanna	The quest for the hot (5-10 MK) plasma in the solar corona	Coronal heating; Heating processes in flares/CMEs	I-2, II-4, II-6	(E)UV and X-ray spectroscopy, spatially resolved
7	Christe	Solving the Coronal Heating Problem using X-ray Microcalorimeters	Coronal heating; Heating processes in flares/CMEs	I-2	X-ray spectroscopy, spatially resolved (soft)
8	Narukage	White paper of the "soft X-ray imaging spectroscopy"	Coronal heating; Heating processes in flares/CMEs; Probing flare processes via particle acceleration	I-1, I-2, II-4, II-6	X-ray spectroscopy, spatially resolved
9	Berrilli	ADAHELI PLUS: Near Infrared spectropolarimetric imaging of 3d atmosphere and X-ray polarimetric measurements	Coronal heating; Solar dynamo and magnetic dynamics; Solar wind acceleration	I-1, I-3, I-4, I-5, II-6, III-3	Vis/NIR imaging & spectropolarimetry; X-ray polarimetry
10	Morton	Exploring Coronal Dynamics: A Next Generation Solar Physics Mission White Paper	Coronal heating; Solar wind acceleration	I-3, I-5	Coronagraphic spectrometer
11	Reep	Science Objective: Understanding Energy Transport by Alfvenic Waves in Solar Flares	Heating processes in flares/CMEs; Probing flare processes via particle acceleration	II-6	(E)UV spectroscopy, spatially resolved; HXR spectrometer
12	Warren	Science Objective: Understanding Energy Deposition During Solar Flares with Very High Cadence Spectroscopy	Heating processes in flares/CMEs; Probing flare processes via particle acceleration	II-4, II-6	(E)UV spectroscopy, spatially resolved; HXR observations and high-spatial-resolution EUV imaging.

13	Zhao	Simultaneous Multi-Wavelength Observations to Study Sunspots' Subphotosphere and Above-Photosphere Dynamics	Internal structure	I-3, II-5	Magnetograph, high resolution
14	Plowman	White Paper: Coronal Sentinel	Magnetic energy buildup leading to eruptions; Space weather monitoring	I-5, I-6, II-1, II-2, II-3	Magnetograph, stereoscopic; EUV imager; Coronagraphic spectropolarimeter
15	DeLuca	NGSPM Energy Storage in the Solar Atmosphere	Magnetic energy buildup leading to eruptions	I-6, II-1	Magnetograph/spectropolarimeter (including chromospheric) and imager; UV+EUV+SXR spectroscopy and images
16	Ichimoto	Advanced Solar Optical Telescope (ASOT): A space-borne magnetograph for study of solar eruptions	Magnetic energy buildup leading to eruptions	II-1, II-2, II-3	Magnetograph/spectropolarimeter and imager
17	Parenti	Linking the small scales dynamics to the large scales variation of the solar atmosphere	Magnetic energy buildup leading to eruptions; Coronal heating; Solar wind acceleration	I-1, I-2, I-4, I-5, II-1, II-2, II-4	UV spectroscopy, spatially resolved; Magnetograph and EUV imager (full disk)
18	Orozco Suarez	MACHROS: The MAgnetic CHROmosphere Sentinel	Magnetic energy buildup leading to eruptions; Magnetic geometry/topology/reconnection	I-1, I-3, I-5, I-6 , II-2, II-3, II-4, II-6	Magnetograph/spectropolarimeter and imager (chromosphere)
19	Casini	Stereoscopic Magnetometry of the Chromosphere	Magnetic geometry/topology -- chromosphere	I-1, I-5, I-6, II-1, II-2, II-4	Magnetograph/spectropolarimeter, stereoscopic (UV chromosphere)
20	Lin	A Space Coronal Magnetometry Mission	Magnetic geometry/topology/reconnection -- large scale	I-5, I-6, II-1, II-2, II-3, II-4	Coronagraphic spectropolarimeter, stereoscopic
21	Sterling	Solar Explosions Imager (SEIM): A Next-Generation High-Resolution and High-Cadence EUV Telescope for Unraveling Eruptive Solar Features	Magnetic geometry/topology/reconnection -- small scale	I-1, II-2, II-3	UV/EUV imaging
22	Ishikawa	High-Precision Spectropolarimetry in Ultra Violet (UV)	Magnetic geometry/topology/reconnection; Coronal heating	I-1, I-3, I-4, I-5	Spectropolarimeter and imager (UV chromosphere)
23	Peter	Understanding the Upper Solar Atmosphere	Magnetic geometry/topology/reconnection; Coronal heating; Heating processes in flares/CMEs	I-1, I-2, I-3, I-4, II-4	(E)UV spectroscopy, spatially resolved; Magnetograph/spectropolarimeter; coronal imager and spectropolarimeter
24	DeLuca	NGSPM Energetic Events in the Solar Atmosphere	Magnetic geometry/topology/reconnection; Heating processes in flares/CMEs; Probing flare processes via particle acceleration	I-2, II-4, II-6	Coronagraphic spectropolarimeter; EUV+SXR+HXR imaging and spectroscopy
25	Matthews	Non-thermal distributions and energy transport in the solar flares	Probing flare processes via particle acceleration	II-6	UV and X-ray spectroscopy, spatially resolved; Magnetograph/spectropolarimeter and imager
26	Shih	Ion Acceleration in Solar Eruptive Events	Probing flare processes via particle acceleration	II-6	Gamma rays, ENAs, neutrons

27	Christe	Exploring impulsive solar magnetic energy release and particle accleration with focused hard X-ray imaging spectroscopy	Probing flare processes via particle acceleration; Magnetic geometry/topology/reconnection	II-4, II-6	X-ray spectroscopy, spatially resolved (hard)
28	Appourchaux	Exploring the poles of the Sun: POLAR Investigation of the Sun (POLARIS+)	Solar dynamo and magnetic dynamics; internal structure; irradiance; space weather monitoring	II-1, II-2, II-3, III-1, III-2, III-4	Magnetograph, White-light coronagraph; EUV imager; UV spectrograph; TSI monitor -- out-of-ecliptic
29	Vourlidas	Solar Polar Diamond Explorer (SPDEx): Understanding the Origins of Solar Activity Using a New Perspective	Solar dynamo and magnetic dynamics; internal structure; magnetic topology/geometry/ reconnection - large scale; solar wind acceleration; Irradiance; Space weather monitoring	I-5 , II-3, II-6, III-1, III-2, III-4	Magnetograph, Coronagraph, EUV imager, Heliospheric imager, TSI monitor, UV spectrograph, in situ measurements -- , out-of-ecliptic
30	Judge	The need to move far from Earth	Solar dynamo and magnetic dynamics; Space weather monitoring	I-4, I-5, II-1, II-3	Magnetograph, coronagraph; out-of-ecliptic or stereoscopic
31	Collet	Lower solar atmosphere and magnetism at ultra-high spatial resolution	Solar dynamo and magnetic dynamics; Coronal heating	I-1, I-2, I-3, II-1, II-2, II-5, III-1, III-2, III-3	Magnetograph/spectropolarimeter and imager (3-meter telescope)
32	Erdelyi	HiRISE: High Resolution Imaging and Spectroscopy Explorer	Solar dynamo and magnetic dynamics; Magnetic geometry/topology/reconnection; solar wind acceleration; Irradiance	I-1, I-2, I-3,1-4, 1-5, II-1, II-2, II-3, II-5, III-1, III-2, III-4	(E)UV and X-ray spectroscopy, spatially resolved; Magnetograph/spectropolarimeter and imager; Coronagraphic spectropolarimeter, heliospheric imager, in-situ measurements, TSI monitor
33	Krasnosselskikh	ICARUS: Investigation of Coronal AcceleRation and heating Up to the Sun	Coronal heating; Internal structure; Solar wind acceleration; Magnetic geometry/topology/reconnection -- large scale	I-5, III-1, III-2, III-3	in situ particles, fields, and waves (ICARUS-1); UV spectrometer, coronal and HXR photometer, magnetograph (ICARUS-2)
34	Brun	All Around the Sun: advocating for coordinated multi-vantage views multi-space missions observations of our star	Space weather monitoring	Concept, rather than science objective: 4pi steradians continuous observations of essentially all kinds of solar output	All kinds of instruments, stereoscopic

Chapter Three: Science Objectives and Tasks

3.1 Description of Objectives

To identify the science objectives of the NGSPM, the SOT used various sources. These included discussions within the Team, community input (in the form of white papers) and the Solar-C proposal of 2015. This set of objectives formed the basis for the selection of the most compelling scientific problems to be addressed by the NGSPM.

All candidate objectives were subjected to a thorough evaluation to assess their interest, timeliness, and scientific/technical feasibility. The following specific criteria were considered by the SOT:

1. Relevance to NASA/JAXA/ESA objectives
2. Scientific impact on solar physics
3. Scientific impact on other disciplines and research fields
4. Inability of current/planned missions and ground-based facilities to accomplish the objective
5. Need for space observations
6. Maturity of technology -- measurements can actually be made
7. Maturity of methodology -- data can be inverted to get findings
8. Widespread interest within the solar physics community

The SOT verified that the objectives are aligned with NASA/JAXA/ESA interests (criterion 1), as set forth in the corresponding agency programs or relevant documents (e.g., US 2013-2022 Decadal Survey in Solar and Space Physics, ESA's Cosmic Vision Programme, JAXA's long-term strategy for space science in Japan). With this requirement cleared, the main criteria leading to the final selection of objectives for the NGSPM were their scientific merit and expected impact (2), the inability of current/planned missions and ground-based facilities to address the relevant scientific problem (4), and the need for space-based measurements (5). Slightly lower weight was given to the maturity of technology and methodology (6, 7). However, no objective was adopted unless the feasibility of the measurements and their interpretation was established. The remaining criteria were regarded as of somewhat lower importance (3, 8).

Special attention was paid to assessing whether the scientific objectives could be achieved with existing or planned facilities, either on the ground or in space. The SOT acknowledges that some of the questions may partly be solved using ground-based observations, but those measurements are very often complementary rather than overlapping. For truly transformative results, the benefits of space - in particular access to UV, EUV and X-ray spectral windows, stability, large fields of view and long-duration measurements - turn out to be essential in nearly all cases. To be specific, the next generation of 4-m class ground-based solar telescopes will provide observations of the photosphere and chromosphere at ultra-high spatial resolution, but this will be over relatively small fields of view and with incomplete coverage in time. A space-based platform makes it possible to observe, monitor and track larger fields of view for long periods of time, as well as providing simultaneous access to the transition region and the corona for seamless observations of the entire solar atmosphere. These capabilities are particularly important for studying the long-term evolution of both the quiet Sun and active regions. For example, assessing coronal heating by braiding necessitates following individual magnetic elements for long periods of time over large fields of view to cover several supergranules, which can only be achieved from space. Understanding the evolution of, and energy build-up in, a flaring active region requires continuous tracking of the whole region from emergence - typically taking 1-2 days - through the onset and development of strong flaring activities once the majority of flux has emerged. Synergies with Solar Orbiter, the Parker Solar Probe, the Daniel K. Inouye Solar Telescope or other ground-based facilities were considered an asset in almost all cases.

Only those objectives that fulfilled a majority of criteria to a significant degree were retained. The evaluation process led to the selection of three primary scientific objectives for the NGSPM: (I) Formation mechanisms of the hot and dynamic outer atmosphere, (II) Mechanisms of large-scale solar eruptions and foundations for predictions and (III) Mechanisms driving the solar cycle and irradiance variation -- each with multiple sub-objectives.

The full list of objectives and sub-objectives is presented in Table 3-1 below, along with key observational tasks that would enable a forthcoming solar physics mission to make progress on the scientific objectives. The tasks were identified through Team discussions and also via input from the community. A brief summary of each sub-objective was drafted by the Team to delineate the current state of knowledge within solar physics and the main open questions. These summaries are collected in **Appendix B**, where the tasks and associated measurements are also given.

Table 3-1: Science Objectives, sub-objectives, and tasks

	Sub-objectives	Tasks
I: Formation mechanisms of the hot and dynamic outer solar atmosphere.		
I-1	understand the formation mechanism of chromospheric fine scale structures and their influence on the corona	I-1-1: magnetic topology and dynamics at footpoints of jets
		I-1-2: MHD waves, role in driving jets and heating chromosphere
		I-1-3: coronal response to jets
I-2	test the nanoflare heating hypothesis	I-2-1: occurrence spectrum at better sensitivity
		I-2-2: very hot component and non-thermal motion
		I-2-3: thermal response to braiding
		I-2-4: formation of braiding, relation to magnetoconvection
I-3	test the wave heating hypothesis	I-3-1: energy flux, propagation and mode conversion of MHD waves
		I-3-2: excitation of MHD waves
		I-3-3: location and mechanism of wave dissipation
I-4	understand role of flux emergence in atmospheric heating	I-4-1: topology of emerging flux and interaction with surroundings

		I-4-2: flux emergence/cancellation rates
		I-4-3: transfer and release of energy carried into atmosphere by emerging flux
I-5	identify sources and driving mechanisms of the solar wind	I-5-1: magnetic field geometry at the base of the solar wind
		I-5-2: coronal magnetic field configuration
		I-5-3: wind mass and energy supply due to spicules in different regions
		I-5-4: source regions of solar wind using mass fractionation
		I-5-5. acceleration profile
		I-5-6: wave energy in the corona
		I-5-7: resonant heating; anisotropy, FIP dependence
		I-5-8: plasma parameters in the large-scale corona
I-6	understand the formation mechanism of prominences	I-6-1: magnetic field structure
		I-6-2: prominence mass supply/circulation
		I-6-3: magnetic conditions of formation and destabilization
II: Mechanisms of large-scale solar eruptions and foundations for predictions		
II-1	measure energy build-up in flaring and CME regions	II-1-1: large scale field configuration by extrapolation from surface magnetic field
		II-1-2: Poynting flux through the photosphere
		II-1-3: dark filament structure and development prior to eruption
		II-1-4: coronal magnetic field in eruptive regions
II-2	identify the trigger mechanism of flares and CMEs	II-2-1:chromospheric fine structure evolution
		II-2-2: reconfiguration of coronal magnetic field
		II-2-3: change of electric current system
II-3	understand the evolution and propagation of CME and their effect on surrounding corona	II-3-1: kinematics of CME including rotation, acceleration, and interaction
		II-3-2: reconnection during the eruption
		II-3-3: shocks and other waves associated with CME
II-4	understand the processes of fast magnetic reconnection	II-4-1: discontinuities in the magnetic field
		II-4-2: key parameters determining reconnection rate
		II-4-3: temperature, density, velocity structures associated with reconnection

II-5	understand the formation of (delta) sunspots	II-5-1: origin and properties of subsurface field
		II-5-2: coupling of convection and surface fields
		II-5-3: sheared polarity inversion lines and related coronal structures
II-6	understand particle acceleration and flare energy transport	II-6-1: electron and ion distributions in corona and chromosphere
		II-6-2: electrons in flight through solar atmosphere
		II-6-3: dynamic response of the lower atmosphere
		II-6-4: evidence of Alfven waves transporting energy
III: Mechanisms driving the solar cycle and irradiance variation		
III-1	measure flow structures in the solar convection zone	III-1-1: internal flows at high latitudes
		III-1-2: meridional flows in the deep convection zone
		III-1-3: global convection features
III-2	locate and trace the global magnetic flux in the Sun	III-2-1: acoustic anomaly in the deep convection zone
		III-2-2: flows in flux tubes near tachocline
		III-2-3: origin of polar magnetic fields
III-3	quantify the turbulence in the dynamo mechanism	III-3-1: small-scale helicities in the photosphere
		III-3-2: kinetic/magnetic energy in turbulent convection
III-4	understand the mechanism of solar irradiance variations	III-4-1: brightness and elemental structures in UV sources
		III-4-2: Model construction of TSI and SSI
		III-4-3: long-term variability of photometric intensity
III-5	explore the deep internal structure of the Sun	III-5-1: Detection of g-mode for understanding its excitation and travel of waves in the Sun (and for investigating the solar core)

Nearly half of the sub-objectives identified for the NGSPM are new compared with the original Solar-C proposal (8 out of 17). These include I-4, II-3, II-5, II-6, III-1, III-2, III-3, and III-5. The rest of the sub-objectives were present in the Solar-C proposal, and remain compelling. However, some of these have been substantially updated to take into account recent developments in solar physics (I-5, II-1, II-2, II-4, III-4).

3.2 Required measurements and Notional Instruments

Each of the tasks listed in Table 3-1 implies certain requirements for instrumental capabilities, such as spatial resolution, wavelength range, temperature sensitivity, etc. The measurements are to be carried out by science instruments, the details of which are normally defined in mission proposals. Each sub-objective in Table 3-1 has multiple key observations, and several sub-objectives in the list share the same key observations, so that the Team has identified notional 'strawman' instruments to execute each observation. As a result, it becomes clear how many instruments are required for each sub-objective. Table 3-2 provides the list of key observations (OBS-##) and notional instruments (T-##). These notional instruments include several possible implementations that will need to be defined in mission proposals. One example is instrument T-01, 0.1" Photospheric magnetograph, that could be either a filter based instrument or a scanning spectro-polarimeter or a combination of both types of instruments. In some cases, utilization of key technologies and thoughtful selection of some observational parameters such as observing wavelengths can enable multiple requirements to be met by a single instrument. Independent multiple instruments may be realized as a single payload package in a proposal responding to a future AO. For example, T-01, T-04 and T-05 may be combined into a single instrument, and T-09 might be upgraded to cover the capabilities of T-05 by extending the wavelength range to the UV where chromospheric spectral lines are formed.

Note that the "possible wavelength range" in Table 3-2 is neither exclusive (instruments in neighboring wavelength ranges may be just as successful), or necessary (i.e. instruments need not operate in all the listed wavelength bands).

Table 3-2: Notional instruments for required measurements, motivated by the science objectives (see **Appendix B**).

Required Measurements		Notional Instrument		Spatial resolution	Temporal resolution	FOV	Possible Wavelength range
ID	Description	ID	Instrument Type				
OBS-1	Imaging observations of the photospheric radiance at high resolution of 0.1 arcsec Imaging observations of the photospheric velocity and magnetic fields at high resolution of 0.1 arcsec Spectro-polarimetric observations of the photospheric velocity and magnetic fields at high resolution of 0.1 arcsec	T-01	0.1" photospheric magnetograph	0.1"	10 s	>200"	NUV, visible, IR
OBS-2	Imaging observations of the photosphere and chromosphere at resolution of 0.2 arcsec	T-02	0.2"-0.5" photospheric & chromospheric	0.2"-0.5"	10 s	>300"	NUV, visible, IR

	Imaging observations of the photospheric (0.3”) and chromospheric (0.5”) velocity and magnetic fields		imaging magnetograph				
OBS-3	Full-disk observations of the photospheric velocity and magnetic fields at resolution of 1 or a few arcsec	T-03	Full-disk photospheric magnetograph	~1"	1 min	full disk	Visible
OBS-4	Imaging observations of the chromosphere at high resolution of 0.1 arcsec Imaging observations of the chromospheric velocity and magnetic fields at high resolution of 0.3 arcsec or better	T-04	0.1"--0.3" chromospheric imager and magnetograph	0.1" (imaging, velocity) 0.3" (high-precision magnetic field)	10 s	>200"	NUV, UV, visible, IR
OBS-5	Spectroscopic observations of the chromosphere at high resolution of 0.1 arcsec	T-05	0.1" chromospheric spectrograph	0.1"	10 s	>300"	UV
OBS-6	Full-disk observations of the chromospheric radiance at resolution of 1 arcsec	T-06	Full-disk chromospheric imager	~1"	10 s	full disk	UV
OBS-7	Imaging observations of the warm corona at high resolution of 0.2 arcsec Imaging observations of the hot corona at high resolution of 0.6 arcsec	T-07	0.2"--0.6" coronal imager	0.2" (EUV), 0.6" (SXR)	10 s	>300"	EUV, SXR
OBS-8	Imaging observations of full-disk coronal activity	T-08	Full-disk coronal imager	0.3"	10 s	full disk	EUV, SXR
OBS-9	Spectroscopic observations of the corona and transition region at high resolution of 0.3 arcsec	T-09	0.3" coronal/TR spectrograph	0.3"	1 sec	>300"	EUV, SXR

OBS-10	Spectroscopic imaging of superhot and nonthermal coronal emission produced in solar flares with a low background	T-10	High-energy spectroscopic imager	2"-5"	100 msec	>300"	HXR
OBS-11	Imaging observations of coronal density structures between ~1.1 and ~15 solar radii above the limb	T-11	Large-angle coronagraph	~2"	1~5 min		Visible
OBS-12	Synoptic coronal vector magnetic field and topology (1"-2"), higher time resolution CME precursor evolution (10").	T-12	Coronagraphic polarimeter	synoptic (1-2") ; CME precursor~ 10"	synoptic-1-5 minute ; CME precursor ~ 1 hr	global	Visible, IR, UV
OBS-13	Spectroscopic observations of the coronal velocity in the acceleration site of solar winds (2Rs < R < 5Rs)	T-13	Coronagraphic spectrograph	~1"	~1 hr	>300"	UV, visible
OBS-14	Imaging observations of the extended corona and heliosphere	T-14	Heliospheric imager	~1 deg	~1 hr	global	Visible
OBS-15	Photometric observations of the Sun as a star	T-15	Total Solar Irradiance (TSI) and Solar Spectral Irradiance (SSI) monitors	~1 deg	1min	full disk	All for TSI; UV for SSI

3.3. Choosing a path for NGSPM

Each of the SOT members assessed the objectives and sub-objectives based on the eight criteria listed in Section 3.1 above and the results were discussed in detail within the Team. Overall the evaluations of each team member were in remarkable agreement. Some criteria displaying larger discrepancies were subject to specific scrutiny. Most of the discrepancies were found to be caused by the different assumptions and considerations made by the members, and thus could be removed easily by agreeing upon the terms of evaluation.

The SOT acknowledges that, although the full range of science objectives in Table 3-1 are compelling, supported by the community, and technically feasible within the next decade, no single mission could achieve all the proposed objectives. Thus, the Team found it useful to consider conceptual groupings of the objectives to clarify how the most science could be achieved within expected constraints and resources.

The SOT's review of the current state of heliophysics, including recent discoveries and developments, indicates that the discipline's scientific objectives can be roughly divided into two avenues: physical mechanisms on elemental (small) scales, versus global processes affecting/involving large fractions of the solar interior and/or atmosphere, and propagating into the solar wind. This division is imperfect and subjective, as the processes are certainly not decoupled. However, for the purposes of planning a mission to carry a suite of instruments, it is necessary to consider the physical scales of the observables, and this 'bimodal' division is useful. Such a viewpoint is supported by the input from the white papers. It is the sense of the SOT that the better near-term opportunity for breakthrough discoveries by the Next Generation Solar Physics Mission will be achieved through the former avenue, probing beyond the state of our present spatial and temporal resolution. Global, multi-vantage observations are scientifically compelling, but also more technically challenging.

Nevertheless, we acknowledge that both avenues, "global" and "elemental", have distinct merits. We now briefly review these merits before presenting a prioritized, notional instrumentation suite for the elemental avenue in section 3.4.

Table 3-3: Global-scale science questions addressable with multi-vantage observations

Scientific motivation	**Orbit/vantage**	**Instruments required**
Constrain models of the solar interior, including solar-cycle variation	Sustained away from Sun-Earth line -- either in-ecliptic or polar/high latitude	Doppler-magnetograph (T-03)
Constrain magnetic fields and flows at poles, including solar-cycle variation	Sustained polar/high latitude	Doppler-magnetograph (T-03)
Full spherical magnetic boundary evolution	Sustained away from Sun-Earth line -- either in-ecliptic, or polar/high latitude in both hemispheres	Doppler-magnetograph (T-03)
Earth-directed CME and solar wind analysis and monitoring (monitoring places requirement for sustained measurements)	(Sustained) away from Sun-Earth line -- either in-ecliptic or polar/high latitude. High-latitude view enables direct Bz measurement by polarimetric coronagraph.	White light coronagraph/ heliospheric Imager (T-11), EUV/SXR imager (T-08), polarimetric coronagraph (T-12) coronagraphic spectrograph (T-13) heliospheric imager (T-14)
Constrain models of 3D magnetic fields, e.g., through stereoscopy/tomography, vector ambiguity resolution (sustained measurements enable synoptic models)	(Sustained) away from Sun-Earth line -- either in or out of ecliptic	Chromospheric spectropolarimeters (T-02), polarimetric coronagraph (T-12), EUV imager (T-08)
Latitudinal variation of solar irradiance over solar-cycle time scales	Sustained polar/high latitude	Total solar irradiance monitor (T-15), UV spectrograph (T-05)

3.3.1 Global, multi-vantage observations

About a quarter of the white papers (9/34[1]) argued for the large benefit of vantage points away from the Earth-Sun line, including both in or near-ecliptic stereo views or out-of-the-ecliptic high-latitude views. The science motivating these observations is compelling. Table 3-3 highlights two major gaps in our current observational capabilities that could be addressed by such observations. First, although the STEREO and Ulysses missions moved away from Earth-Sun line, neither observed the solar magnetic fields and flows needed for progress on several key science topics enabled by these vantages. Solar Orbiter will for the first time obtain remote sensing observations out of the ecliptic. However, like STEREO, Ulysses, and the Parker Solar Probe, it will not maintain a sustained vantage point -- a second requirement on several science goals. Sustained polar/high-latitude views (which, depending on the science goal, may range from multiple months to the solar cycle) can be achieved by a constellation of spacecraft or by a single spacecraft on a carefully selected orbit.

Transformative progress would certainly be made possible by sustained, multi-vantage views. Through the white papers, the community suggested a variety of implementation options, addressing required technologies and orbits, and emphasizing the need for constellations of spacecraft and potentially the use of a communication hub (mother ship). Such comprehensive implementation schemes likely exceed the resources available for a NGSPM on the timescale of the next decade. However, international coordination over the upcoming decades is desirable to enable the development of an optimized armada of spacecraft that would fill critical vantage gaps, and thus obtain a truly global understanding of the Sun.

3.3.2 Elemental-scale activity

Solar activity on the smallest length and time scales illuminates fundamental physical processes, often with less complex interactions and configurations than larger-scale analogues. For one example, active region microflares can be considered as scaled-down versions of solar flares, with much simpler magnetic topologies; and the time profiles of their brightenings, and their energy budgets, can be analyzed and reproduced with models much more simply than flares that encompass whole active regions. Similarly, recent observations demonstrate that waves can be observed propagating along the bodies of individual spicules, such that time-varying wave amplitudes and phase speeds can be monitored; such quantitative precision is lost in studies of unresolved ensembles of strands in coronal loops, and is possible only with adequately high spatial and temporal resolution. To empirically quantify the fluxes of energy and mass, and to accurately characterize the dynamics and morphology relevant to fundamental physical mechanisms which lie at the heart of the larger events, it is necessary to resolve the scales on which such mechanisms occur.

Game-changing discoveries may be found on these elemental scales, such as the nature of magnetic stresses resulting from braiding of magnetic field lines; the magnetic topology at the footpoints of spicules, jets, and prominences; the transport of energy via Alfvén waves in flares; and the development and effects of turbulence in all levels of the solar atmosphere. Specific examples of sub-objectives for which progress will substantially benefit from observations with increased resolution include “Processes of fast magnetic reconnection” (II-4), “Identify[ing] the trigger mechanism” (II-2), and nearly all of the sub-objectives relating to Objective I “Formation mechanism of the hot and dynamic outer solar atmosphere”. Most of

[1] Appourchaux; Brun; Casini; Judge; Krasnosselskikh; Lin; Orozco Suárez; Plowman; Vourlidas

the Tasks for these science topics make use of wavelengths that are not accessible from the ground or require long-duration observations in a stable, seeing-free environment, necessitating observations from a space platform.

There is every reason to believe that a higher-resolution focus for NGSPM will be rich scientifically. Recent missions such as the Sunrise balloon-borne observatory (0.1" resolution), Hi-C sounding rocket (0.2" resolution EUV imager), IRIS (0.3" resolution UV spectrograph) and Hinode (0.3" resolution photospheric spectropolarimeter) have yielded a disproportionate number of results and publications. Given current constraints, continuing to increase resolution is both feasible and well-suited to NGSPM near-term opportunities. In particular, we note that a great number of high-priority tasks in Table 3-1 can be achieved with a specific, modular suite, as we now describe.

3.4 Team Conclusion: An optimal instrumentation suite for elemental science

In consideration of a minimum set of instruments with which NGSPM can address the greatest number of high-priority Tasks consistent with the objective of small length- and time-scale activity, we find that a majority of the key required measurements can be met with a suite of instruments including:

1. 0.3" coronal/TR spectrograph (T-09)
2. 0.2"- 0.6" coronal imager (T-07)
3. 0.1"- 0.3" chromospheric imager and magnetograph (T-04)
4. 0.1" photospheric magnetograph (T-01)
5. 0.1" chromospheric spectrograph (T-05)

While other combinations of candidate instruments would likely also produce significant results, the list above represents the smallest set of instruments addressing as many as 32 of the 56 listed Tasks; it is the list of instruments that the SOT feels should receive the highest priority for selection. For completeness, Table 3-4 indicates all the instruments that were deemed by the SOT to be needed for each of the Tasks.

Table 3-4 also serves to emphasize the necessity and value of combinations of instruments: certain instruments like the coronal/TR spectrograph need to be operated in tandem with an imager for context and pointing knowledge. Indeed, the great majority of the Tasks in Table 3-4 require some combination of instrumentation for closure or significant progress. Thus the strawman suite of instruments considered above has been optimized to maximize the scientific return from the NGSPM. Asterisks in Table 3-4 denote the Tasks that are fully addressed by the strawman suite of instruments. Obviously some of the Tasks are addressed incompletely (e.g., II-3-3), and some not at all (e.g., I-5-5), due to the lack of some needed capability, for instance a full-disk imager. It is anticipated that the NGSPM will build upon synergies with other missions that will have such complementary capabilities (e.g., SDO or its follow-on) and with ground-based telescopes to accomplish additional measurements. Conversely, it is anticipated that the NGSPM will complement these facilities by granting access to the upper solar atmosphere. Indeed, the NGSPM is timely in view of the next generation of large solar telescopes coming online in the next decade (DKIST will see first light in 2020, and EST first light is planned for 2026). The next section of this report (Section 4) considers specific potential mission architectures based on the suite of instruments listed above.

Table 3-4: Instruments contributing to each Task. Asterisks denote the tasks that are fully addressed by the strawman suite of instruments. Note that some tasks require multi-vantage observations as described in Table 3-3.

Task	Candidate Instruments Needed
I-1-1*: magnetic topology at footpoints of jets	T-01, T-04
I-1-2*: shock waves as driver of jets	T-01, T-04, T-05, T-07, T-09
I-1-3*: coronal response to jets	T-05, T-07, T-09
I-2-1*: occurrence spectrum at better sensitivity	T-07, T-09
I-2-2*: very hot component and non-thermal motion	T-07, T-09, T-10
I-2-3*: relation to braiding	T-07, T-09
I-2-4*: formation of braiding	T-01, T-04, T-07
I-3-1*: propagation; energy flux, mode conversion	T-04, T-05, T-07, T-09
I-3-2*: excitation;	T-01, T-04, T-07, T-09
I-3-3*: dissipation	T-04, T-05, T-07, T-09
1-4-1*: topology of emerging/cancelling flux	T-01, T-04, T-05, T-07, T-09
I-4-2*: emergence rate	T-01, T-04
I-4-3*: transfer and release of energy in atmosphere	T-01, T-04, T-05, T-07, T-09
I-5-1: magnetic field geometry at the base	T-01, T-03, T-04
I-5-2: coronal magnetic field	T-12
I-5-3*: mass and energy supply from spicules	T-07, T-09
I-5-4*: source region of wind	T-09
I-5-5. acceleration profile	T-11, T-13
I-5-6*: wave energy in the corona	T-07, T-09
I-5-7: resonance heating; anisotropy, FIP dependence	T-09, T-13
I-5-8: plasma properties in the large-scale corona	T-11, T-12, T-13
I-6-1*: magnetic structure	T-01 or T-02, T-04
I-6-2*: mass supply	T-04, T-05, T-07, T-09
I-6-3*: condition of formation	T-01 or T-02, T-04
II-1-1: extrapolation from surface magnetic field	T-01 or T-02, T-03, T-04
II-1-2*: Poynting flux through the photosphere	T-01 or T-02
II-1-3*: dark filament	T-01 or T-02, T-04, T-05
II-1-4: coronal magnetic field	T-12, T-08
II-2-1*: change in chromosphere	T-04, T-05
II-2-2*: coronal reconfiguration	T-07 or T-08, T-09, T-12
II-2-3*: change of electric current system	T-01 or T-02, T-04, T-07 or T-08, T-12
II-3-1: kinematics including rotation, acceleration of CME	T-05, T-07, T-08, T-11, T-13, T-14
II-3-2: reconnection during the eruption	T-07, T-08, T-09, T-10, T-11, T-13
II-3-3: shocks and other waves associated with CME	T-07, T-08, T-09, T-11, T-13, T-14
II-4-1*: discontinuity of magnetic fields	T-04
II-4-2*: key parameters determining reconnection rate	T-04, T-07, T-09
II-4-3*: temperature, density, velocity associated with reconnection	T-07, T-09
II-5-1: subsurface field	T-03
II-5-2*: convection and surface field	T-01 or T-02, T-04
II-5-3: sheared polarity inversion lines and related coronal structures	T-01, T-03, T-04, T-05, T-07, T-09
II-6-1: evolution of electron and ion distributions	T-07, T-10
II-6-2: electrons in flight through solar atmosphere	T-07, T-10
II-6-3: dynamic response of the lower atmosphere	T-04, T-05, T-09, T-15

II-6-4*: evidence of Alfven waves transporting energy	T-04, T-05, T-07, T-09
III-1-1: Internal flows at high latitudes	T-03
III-1-2: meridional flows in deep convection zone	T-03
III-1-3: Search for global convection features	T-03
III-2-1: acoustic anomaly in the deep convection zone	T-03
III-2-2: Detection of a flow in flux tube near tachocline	T-03
III-2-3: Origin of polar magnetic fields	T-01, T-03
III-3-1*: small-scale helicities in the photosphere	T-01
III-3-2*: kinetic/magnetic energy in turbulent convection	T-01
III-4-1*: brightness and elemental structures in UV sources	T-01
III-4-2: Model construction of TSI and SSI	T-03, T-06, T-15
III-4-3: long-term variability of photometric intensity	T-03, T-06, T-15
III-5-1: Detection of g-mode for understanding its excitation and travel of waves in the Sun (and for investigating the solar core)	T-03

Chapter Four: Assessing possible mission designs

4.1. Top-level priority of instruments

The Charter of the NGSPM-SOT assigns the task of suggesting possible mission profiles that could satisfy the science objectives identified by the SOT, within the likely available resources. In this Chapter, we consider several possible mission profiles, appropriate to either a single large mission, or a constellation of small- or mid-class spacecraft. Although the principles that the SOT used to suggest instruments for each of these mission profiles could be applied to any set of instruments, in this chapter, we focus on permutations of the five suggested notional instruments discussed in Section 3.4, namely

1. 0.3" coronal/TR spectrograph (T-09)
2. 0.2"-0.6" coronal imager (T-07)
3. 0.1"-0.3" chromospheric imager and magnetograph (T-04)
4. 0.1" photospheric magnetograph (T-01)
5. 0.1" chromospheric spectrograph (T-05)

Of these 5 instruments, T-04, T-01, and T-05 can potentially be merged into a single telescope with focal plane instruments, when suitable wavelengths in near IR, visible and near UV are chosen in the design. Therefore, in the subsequent sections, the SOT has considered some mission concepts for accommodating the following three instruments.

1. 0.3” coronal/TR spectrograph (T-09)
2. 0.2"-0.6” coronal imager (T-07)
3. 0.1” chromospheric/photospheric magnetograph/spectrograph (T-01/04/05)

4.2. Mission concepts

The three instruments outlined above could be realized in one single large mission. If not, they could be realized by forming a constellation of small/mid-class missions, as described below.

<u>Mission Concept 1: Large mission design</u>

This design concept is to have T-09, T-07, and T-01/04/05 instruments on a single platform. Significant contributions from all the agencies would be required for this mission. The preferred orbit for this mission is geosynchronous, for uninterrupted solar observing (much of the year) and high telemetry. There are significant scientific and operational advantages to the large mission design, including the following:

1. All instruments are mounted on a single bus and hence launched and operated simultaneously.
2. Instruments are designed from the start to be complementary, with tradeoffs optimized for obtaining the required measurements.
3. Mission operations are integrated, ensuring coordinated scientific observing and cost-saving by avoiding duplication of ground systems.

4. Use of a single spacecraft bus, launcher, and project management offices may reduce total costs.

Mission Concept 2: Constellation of small/mid-class missions

This mission concept is to form a constellation of small or middle-class satellites for realizing the three instruments, by utilizing spacecraft of JAXA, NASA, and/or ESA (including ESA member states). Section 4.6 describes the programs of the agencies for missions of this class, all of which allow for international contributions to a mission led by one agency.

The merit of this mission concept is to increase the possibility that some of the instruments are launched as early as possible in the mid-2020's, but a risk is that the scientific synergy among the three instruments will be limited unless there is significant overlap in observing time of the missions. Moreover, another key point is how well the ideal performance required for the three instruments can be realized with the limited resource of small and middle-class missions. Orbits for these spacecraft could be low-Earth Sun-synchronous similar to Hinode and IRIS. However, significantly more telemetry will be required than for either of those missions.

4.3. Description of the Instruments

Before discussing possible mission design concepts and international coordination, this section describes strawman designs for the three instruments and their approximate scale.

4.3.1. Design example: T-09 (0.3 arcsec coronal/TR spectrograph, Table 4-1)

About a quarter of the community white papers (8 of 34, Young; Peter: Ugarte-Urra; Imada; Warren; Reep; Klimchuk; Del Zanna) argue the importance of high-throughput EUV spectroscopy and many of them suggest that an FUV/EUV spectroscopic telescope is ideal for the proposed science topics, not only in coronal heating, but also in flare dynamics. Key instrument performance requirements from the science objectives are: 1) high throughput for achieving much improved high temporal resolution, 2) a wide and seamless coverage of plasma temperature from 0.1 MK to 10 MK, and 3) high spatial resolution (0.3") for distinguishing elementary magnetic structures in the upper atmosphere.

The strawman design concept is a 30cm single mirror telescope with a slit and grating system, covering EUV and FUV wavelength bands where spectral lines are available for diagnosing a wide range of plasma temperature from 100 kK to about 20 MK. With appropriate wavelength choices in EUV and FUV, T-09 could be merged with T-05 to cover from the upper chromosphere (15 kK) through the TR and to the corona in a single instrument. If the instrument is more focused on higher temperature plasma for nanoflare heating and flare diagnostics, SXR is also possible. The instrument throughput is required to be about one order of magnitude higher than previous EUV spectrometers such as Hinode/EIS, SoHO/SUMER. The requirement for the high spatial resolution (0.3") makes the instrument long, of order 4 meters.

Table 4-1: Key performance of Strawman T-09 (0.3 arcsec coronal/TR spectrograph)

performance		rationale
Temperature coverage	10^4–$10^{7.3}$ K	From upper chromosphere and TR to flaring corona
Spatial resolution	0.3”	Coronal loop fine structure
Time resolution	~1.0 sec ~ 10min	Flare dynamics MHD time scale of fine structures, evolution of AR
Field of view [EW×NS]	>240”×240”	Large active region and surroundings
Continuous time coverage	5 hours (high cadence observation) 2 weeks (active region evolution)	Multi-hour wave studies at high cadence. Maximum uninterrupted timescale for AR evolution is 2 weeks.
Photometric accuracy	$dI/I < 0.1$ (corona)	

4.3.2. Design example: T-07 (0.2 - 0.6" Coronal Imager, Table 4-2)

A coronal imager instrument design has been studied extensively in the US. The AIA and SUVI instruments now flying are full disk examples, and the Hi-C rocket payload demonstrated that a normal incidence telescope can achieve spatial resolution of 0.2 arcseconds or better. The value of such a capability goes far beyond providing context for a coronal spectrometer, as the science objectives show: studies of loop braiding, waves, hot plasma, coronal connectivity, flare kernels and ribbons, etc. all require high resolution coronal images. Exposure times of a few seconds (less in flares or bright active regions) are sufficient, so high-cadence, multi-wavelength observations will be possible if the mission has enough telemetry (or high-rate data storage onboard). There is considerable freedom in normal-incidence EUV design to choose the number of telescopes and/or the segmentation of the telescope mirrors to observe multiple wavelength bands sampling coronal temperatures of 0.7 - 20 MK; optional additions might be transition region and photospheric or low chromospheric images in the UV. Image stabilization and sensitive cameras suitable for this instrument have already been demonstrated in SDO/AIA, Hi-C, IRIS, and Proba-2/SWAP, so there are no technological barriers to overcome. Primary mirror diameter(s) in the 20-25 cm range and instrument length(s) of 2-3 m can be expected. A complementary approach to such an instrument (without replacing the T-09 spectrometer) might be a multi-slit spectrometer with rapid scanning capability. This would not only produce images but also spectra in a few lines for Doppler shifts and line profiles at each pixel, with a cadence of ten(s) of exposures.

An alternate approach to coronal imaging is a grazing-incidence soft X-ray telescope, with a number of selectable focal-plane filters for analysis of plasmas over a range of temperatures. Previous coronal imagers of this type include Yohkoh/SXT, Hinode/XRT, and GOES/SXI. As with the EUV imager considered above, sensitive cameras for soft X-ray telescopes are already available. Sub-arcsecond spatial resolutions are significantly more challenging for soft X-rays, however, largely due to the very tight tolerances on smoothness of the grazing-incidence mirrors and the long focal lengths that would be required. Achieving angular resolutions of 0.3 arcseconds/pixel with a typical X-ray telescope (usually the Wolter Type-I scope) necessitates either enormously long telescope structures (~6 meters), or significant advances in sensor design (3-micron pixels).

Table 4-2: Key performance of T-07 (0.2 - 0.6 arcsec coronal imager)

performance		rationale
Temperature coverage	$10^{5.5}$–$10^{7.3}$ K	From hot TR to flaring corona
Spatial resolution	0.2” (EUV) - 0.6” (X-ray)	Coronal loop fine structure, wave motion amplitudes
Time resolution	~1 sec per image, ~10 sec for all wavelengths	Flare dynamics, MHD time scale of fine structures, evolution of AR
Field of view [EW×NS]	>240”×240”	Large active region and surroundings
Continuous time coverage	5 hours (high cadence observation) 2 weeks (active region evolution)	Time series of waves, fine structure evolution; AR evolution
Photometric accuracy	$dI/I < 0.1$ (corona)	

4.3.3. Design example: 0.1” chromospheric/photospheric magnetograph/spectrograph (T-01/04/05, Table 4-3)

In this NGSPM instrument concept, a 1m aperture telescope achieves spatial resolutions of ~0.1” for photospheric and chromospheric imaging and spectroscopy, and 0.13~0.5” for photospheric and chromospheric magnetic field observations. A diameter of 1 meter is necessary to achieve the required accuracy of polarization measurements in chromospheric lines (3×10^{-4}) at the required spatial sampling (0.25”) and temporal resolution (~10sec). These spatial resolutions will resolve most elementary structures in the photosphere (magnetic flux tubes) and chromosphere (fibrils and jets). With its large field of view (>270”), uniform data quality, continuous time coverage, and high precision spectro-polarimetry at high spatial resolution, the strawman telescope T-01/04/05 will be a highly synergistic instrument with the forthcoming ground-based large solar telescopes (e.g. DKIST) that will achieve an ultra-high (<0.1”) spatial resolution with a limited FOV and shorter time-spans. The focal plane package consists of a filtergraph imager and a spectrograph that conduct imaging and spectro-polarimetric observations in dedicated spectral lines in wavelengths from 380nm (optionally 280nm) to 1100nm.

Table 4-3: Key performance of T-01/04/05

(0.1” chromospheric/photospheric magnetograph/spectrograph)

performance			rationale
Spatial resolution	imaging	0.1” (Photosphere, chromosphere)	Faculae point, ~ photon mean free path in photosphere
	polarimetry	0.13” (Photosphere) 0.25” (chromosphere)	flux tube diameter Chromospheric fibril
Time resolution	~1.0 sec (imaging) ~10 sec (narrow FOV(~40²×40²) magnetograph, dopplergram) ~10min (large FOV magnetograph)		Flare dynamics MHD time scale of fine structures evolution timescale of AR
Field of view [EW×NS]	~90”×90” (photosphere/chromosphere at 0.1” resolution), ~270”×270” (photosphere/chromosphere at 0.3” resolution)		Super granulation Active region, prominence
	>10”×10” (high cadence chromospheric Dopp. mag. Obs)		Size of spicules
Continuous time coverage	5 hours (high cadence observation) 2 weeks (AR evolution)		
Photometric accuracy	$dI/I < 0.03$ (Photo./chrom. Imaging)		
	10^(-3) photospheric magnetic field, 3 x 10^(-4) chromospheric mag. field		dB_L =2 [G], dB_T =70 [G] dB_L =10 [G], dB_T =100 [G]

4.4. Modification of Instruments for constellation of small/mid-class missions

If a constellation of small/mid-class missions is formed to realize the three instruments (T-09, T-07, and T-01/04/05), one (or two) of the instruments will be on board one satellite. Note that the strawman system configuration of a JAXA Epsilon mission is described in **Appendix F**. Considering the resources of small/mid-class missions available, some of the instruments described in the previous section may require a descope of instrument capabilities with some impacts on their ability to achieve the science objectives. This section discusses descope options.

4.4.1. Design example: T-02 (0.2”-0.5” photo/chromospheric imaging magnetograph)

The T-01/04/05 instrument for achieving 0.1" spatial resolution (0.1" chromospheric/ photospheric magnetograph/spectrograph) is difficult to design under the system condition given in **Appendix F** because a 1m telescope cannot be accommodated in the Epsilon envelope. Thus, the instrument is required to become smaller to fit the system. Here we describe a 0.5m class telescope (T-02), for the case of a constellation of smaller/medium platforms. Able to fit into the size and weight constraints of the JAXA Epsilon vehicle, T-02 will be capable of photospheric and chromospheric imaging (0.2") and chromospheric spectropolarimetry (0.5") in visible and near infrared wavelengths (and potentially UV). Compared with the T-01/04/05 instrument, T-02 has a spatial resolution reduced by a factor of 2 and a photon throughput reduced by a factor of 4, and thus will not fully resolve the elementary structures in the photosphere and chromosphere, and takes four times longer integration time to achieve the required photometric accuracy at the same spatial resolution. These disadvantages are partly offset by its larger field of view (~400 arcsec). Due to the above constraints, T-02 will focus on a subset of the scientific objectives that are covered by the T-01/04/05 instrument, i.e., objectives that require a large field of view and continuous long time coverage, such as I-6, II-1, II-2, and II-5.

4.4.2. Design Example: T-09 (0.3 arcsec coronal/TR spectrograph) for Epsilon

The length of the strawman T-09 instrument as described in section 4.3.1 is too long to fit the Epsilon fairing volume with the vertically oriented concept given in **Appendix F**. Possible solutions for optimization are 1) to shorten the instrument length to about 3 meters and mount it vertically on the spacecraft bus (an example is given in Figure E-1); and 2) to keep the original dimensions and mount it obliquely on the side of the spacecraft bus. In solution (1), the spatial resolution may be slightly reduced to 0.35"-0.4" with a slight degradation in the throughput.

4.5. Uniqueness and synergy with other missions

There are a number of solar missions currently operational. These include science missions SOHO, Hinode, RHESSI, SDO, PROBA2, IRIS, as well as the GOES monitoring mission (see **Appendix C**). None of these (except GOES) is currently funded until the first launch opportunity for the Next Generation Solar Physics Mission, although it is reasonable to expect the operation of at least some of these to be extended until there is an overlap. In addition, there are a number of ground-based observatories that may also have potential scientific overlap with NGSPM. Therefore, we briefly consider uniqueness and synergy between these missions, observatories and a putative NGSPM.

SOHO: Only a part of the instruments on SOHO are still providing data. None of those that are still active has any overlap with the instruments on the NGSPM. Therefore, NGSPM will provide unique science compared with SOHO, whose remaining instruments address mainly objectives pertaining to the full Sun, complementing the high-resolution science that NGSPM will carry out.

Hinode: Hinode has a similar profile as NGSPM, but carries smaller instruments with significantly lower spatial resolution and a much more limited coverage of wavelengths and heights in the atmosphere. Thus, the Hinode instruments do not adequately cover the chromosphere and transition region and hence do not meet the requirements posed in Table 3-2, so that they cannot be used to achieve the science goals listed in Table 3-1

RHESSI: This high energy mission (few keV X-rays to a few MeV gamma-rays) has no overlap in wavelength with the NGSPM, though there is some overlap in temperature between the low energy end of RHESSI and the top of the temperature range potentially covered by T-07 and T-09. Used as an imager, RHESSI can achieve spatial resolutions of around 2" and time resolutions of 4 seconds. It is limited to addressing objectives related to particle acceleration and magnetic reconnection, to the extent allowed by its limited spatial resolution. Here the synergistic effects are expected to dominate.

SDO: SDO is a mission concentrating on the continuous coverage of the full solar disk at a spatial resolution of ~1 arc sec. Therefore, it cannot fulfil the science goals identified for NGSPM, making NGSPM unique relative to SDO. Conversely, SDO is complementary to the high resolution instruments proposed for the NGSPM. SDO will provide the context images/magnetograms in which the high resolution data from the various NGSPM instruments will be embedded. There is a very high potential for synergy.

Proba 2: With considerable similarity to SDO as far as coronal imaging is concerned (although with lower cadence and restricted passbands), Proba 2 will also not to be able to reach the science goals of NGSPM, but will be able to work synergistically with it.

GOES: The US national space weather spacecraft have coronal imagers showing the full disk in 6 EUV wavelength bands, with modest resolution. The GOES-16 instrument has just had first light in 2017, and multiple spacecraft will provide this type of data into the 2030's. The spatial resolution of GOES is far too low (around 5 arc sec) to address any of the science goals of NGSPM, but GOES can provide context data.

IRIS: IRIS is a spectrometer and imager, primarily observing the chromosphere and transition region, and therefore it has some overlap with T-04, T-05 and T-09. The NGSPM combination T-04/05 provides significantly higher spatial resolution in the chromosphere, as well as magnetic field measurements (which IRIS is not capable of). Also, IRIS has very little coverage of lines formed in the hot transition region or corona, and thus cannot provide the simultaneous coverage of all temperature ranges of the outer solar atmosphere that T-09 does.

The next solar and/or heliospheric missions due for launch in this decade are Parker Solar Probe, Solar Orbiter, and PROBA-3 with launch dates in this order.

Parker Solar Probe (PSP): PSP will make in-situ measurements of the inner solar wind and outer corona by flying to within 9 solar radii of the solar surface. The only optical instrument it will carry is a heliospheric imager. Hence, it will rely on other spacecraft to provide the context information from remote sensing instruments looking directly at the Sun, including high resolution instruments, as on NGSPM. PSP will probe the microphysics of the outer corona and solar wind in a unique manner, but will miss the connections between different parts of the solar atmosphere that NGSPM will provide.

Solar Orbiter (SO): By orbiting the Sun and leaving the ecliptic, Solar Orbiter will provide solar images, magnetograms and spectra from different vantage points than the NGSPM. This will lead to strong synergies as SO and NGSPM will observe the same regions on the Sun from different directions, allowing them to be probed in a novel manner. SO will also host in situ instruments to sample the inner heliosphere. Unlike NGSPM, SO will be missing all spectroscopic information on the chromosphere, critical for achieving many of the NGSPM's science objectives. Also, the highly elliptical orbit (which allows the highest resolution to be reached only at perihelion) and very limited telemetry available to Solar Orbiter (orders of magnitude less than NGSPM, due to its great distance from Earth) mean that only very limited high resolution data will be downlinked from SO, not sufficient to reach the NGSPM science objectives.

Proba-3: The coronagraph that is at the heart of Proba-3, an ESA formation flying technology demonstration mission, will allow observations of the corona in visible light to very close to the solar surface, greatly expanding the reach of space coronagraphs. This instrument will address largely different science objectives than NGSPM, and will provide unique data, but at vastly lower spatial resolution and outside the solar disk only.

Ground-based Observatories (GBO): There are a number of ground-based observatories around the world that study the Sun. The largest operational solar telescopes (in the optical and infrared) are the NST at the Big Bear Observatory, Gregor on Tenerife, the SST on La Palma and the Chinese 1-m telescope at the Fuxian Lake Observatory. The 4m diameter DKIST is under construction and scheduled to start observing around 2019-2020, with the equally large EST likely following in the 2025-2030 timeframe. In general, ground-based observatories probe only the photosphere and chromosphere (with the exception of DKIST, which also has coronagraphic capabilities). Any overlap will therefore be restricted to the instruments T-01/T-04/T-05 and T-02. In particular, DKIST and EST will address some of the science objectives also being addressed by NGSPM. The higher spatial resolution that DKIST and EST will be able to reach, will give them an edge over T-01/T-04/T-05 and T-02, but at the cost of a more limited FOV (60"x60"), variable spatial resolution (due to seeing) and a much lower duty cycle. As clearly demonstrated by MDI on SOHO, HMI on SDO and SOT on Hinode, even a smaller space-based instrument has unique advantages compared with ground-based observatories. These include the very high duty cycle for nearly uninterrupted observations and long time series, and the possibility of getting seeing-free observations over a large field-of-view. Both, NGSPM and DKIST will be very powerful tools that are strongly complementary to each other. It will therefore be important for NGSPM to observe in conjunction with ground-based observatories, in particular DKIST (and later EST) in order to combine the unique strengths of space- and ground-based resources.

4.6. International coordination

The NGSPM is envisioned as a multi-lateral mission, and as described in the SOT's charter, "is likely to be a Japan-led mission expected to include substantial contributions from the United States and Europe." One of the purposes of this SOT report is to assist the agencies in planning the international coordination needed to realize the NGSPM. In this section we review space programs which have historically been used by the respective agencies to support missions comparable to NGSPM. After summarizing the three agencies' mechanisms, we discuss some possible configurations for a collaborative mission as an exercise for imagining a framework for NGSPM.

4.6.1. JAXA opportunities

JAXA has space programs of three different mission sizes: (1) strategic large missions (300M$ class) for JAXA-led flagship science missions, launched by the H-IIA or the H-III rocket currently in development; (2) medium-sized focused missions (<150 M$ class), launched by the Epsilon rocket; and (3) Missions of Opportunity for contributions to a space mission led by a foreign agency. All are competitive among any science and engineering fields, and international collaborations are recommended. The opportunities for the first and second categories are going to appear roughly three and five times in 10 years, respectively. Possible near-future opportunities for the NGSPM are the strategic large mission for a launch in ~2027 and the competitively-chosen medium-sized mission for a launch in ~2024 and subsequently in two year intervals. A mission proposal to each satellite mission can be submitted by the JAXA working groups that have been established under the JAXA Science/Engineering Advisory Committee.

4.6.2. NASA opportunities

The NASA Heliophysics Division supports flight missions in several classes that may be used for solar physics research, although all are also open to the heliospheric, magnetospheric and upper atmospheric disciplines. Strategic missions are large missions in two lines, the Living With a Star Program and the Solar Terrestrial Probes. The Explorer program has mid-sized missions (MIDEX) and Small Explorers (SMEX), which are highly competitive among all the disciplines of heliophysics. Finally there are Missions of Opportunity (MoO), which can be contributions to missions led by other agencies of the US or foreign countries. The Heliophysics Division recognizes that our science requires many types of observations in many locations, and so a constellation of spacecraft, known collectively as the Heliophysics System Observatory (HSO), is the primary asset for which it is responsible.

Strategic missions are usually defined by the Decadal Survey and the Roadmaps sponsored by the Heliophysics Division. The most recent Decadal Survey (published in 2012) mentioned Solar-C favorably as a worthwhile example of foreign collaborations, which NASA was encouraged in a general way to pursue. However, it did not list Solar-C either as a strategic mission or a specific priority, and so there was no clear mandate for NASA to participate in it or in the EPIC proposal to ESA, despite the widespread recognition that the scientific goals were timely and compelling.

A MIDEX mission can be expected to have a budget in the vicinity of $250 M, based on the Astrophysics MIDEX opportunity of 2016; contributions from other countries or agencies will be permitted as long as they are a modest fraction of the total. The Astrophysics call for proposals listed several available launch vehicles with large capacities in mass and volume to a sun-synchronous low earth orbit or geosynchronous orbit. With a cost cap similar to the 2016 call, a MIDEX might provide two or more of the recommended instruments of this report.

The Decadal Survey also recommended that a Small Explorer mission be started every 2 or 3 years. These are typically missions led by a Principal Investigator, who is responsible for developing all phases of the mission, including spacecraft, instrument(s), ground system, mission operations and data analysis. The cost cap for 2016 proposals was $165M, including a nominal $50M for launch. With this cost cap, a SMEX could provide one of the recommended instruments of this report, perhaps with some reduced capability.

Finally, NASA periodically announces calls for Heliophysics Mission of Opportunity proposals, typically up to $55M for "partner MoOs" that contribute to another agency's mission. This cost cap, which must include the total cost including post-launch mission operations and data analysis, could support a sizable contribution to an instrument for a foreign agency or a small complete instrument. This cost cap for an MoO has been used commonly in the past; but, as far as the SOT is aware, the NASA Heliophysics Division could allow a higher cost cap and/or suggest that it be used for a specific mission such as NGSPM.

4.6.3. ESA opportunities

There are two possible ways to contribute to an international mission within the ESA system. The first is via a proposal to a mission call, either a Medium (M) class mission or a Small (S) class mission call. The missions are selected in competition between all of astrophysics, solar system science, and fundamental physics. Previous M missions have had a budget of up to 550 M€, and are normally ESA led. At the time of writing, it is unlikely that the mission selected from the next M-mission call will be launched before 2030. The most recent S mission (S2) is a bilateral mission with a budget of up to 106 M€ with a maximum of 53 M€ from ESA.

The second way is to propose a contribution to a mission led by another agency via a Mission of Opportunity, which does not have any particular announcement date and can be proposed whenever the opportunity arises. Missions of Opportunity have a cost cap of 50 M€.

In the European system, ESA typically provides support for spacecraft, launch, subsystems, telescopes, operations, but rarely for post-focus instruments. These are funded by national agencies or national funding programs. This means that the total amount of funding available from European sources can, in principle, be larger than the maximum that ESA can provide.

4.6.4. Possible collaborative configurations

A variety of configurations are possible for accommodating the instruments of NGSPM, depending on (among other things) the contributions of the partnering Agencies, the size/scope of the selected instruments, and the decision whether to accomplish the NGSPM mission with a single platform or multiple (presumably smaller) platforms on separate spacecraft. Here we describe some possible collaborative configurations; this is intended not as an exhaustive list, but as only a few examples to illustrate avenues that the SOT has considered as potential recommendations for the agencies.

In Figure 4-1, two possible collaborative configurations are represented. In the first (top row), NGSPM is realized as a single space platform by a JAXA Strategic Large mission, with contributions for instruments, operations, or data processing provided from NASA and ESA. The NASA contribution would likely have to be of a scale similar to a SMEX. In the second configuration (bottom row of Fig. 4-1), the NGSPM instruments are distributed among a constellation to comprise a JAXA Epsilon, a NASA SMEX or MIDEX, and/or an ESA S-class mission. Depending on the resources and priorities of the respective agencies, this configuration could take the form of only two spacecraft, possibly with support from the third agency via a MoO. Regardless of which agencies provide the spacecraft for this latter configurations, at least two space platforms are required to achieve the science objectives of NGSPM.

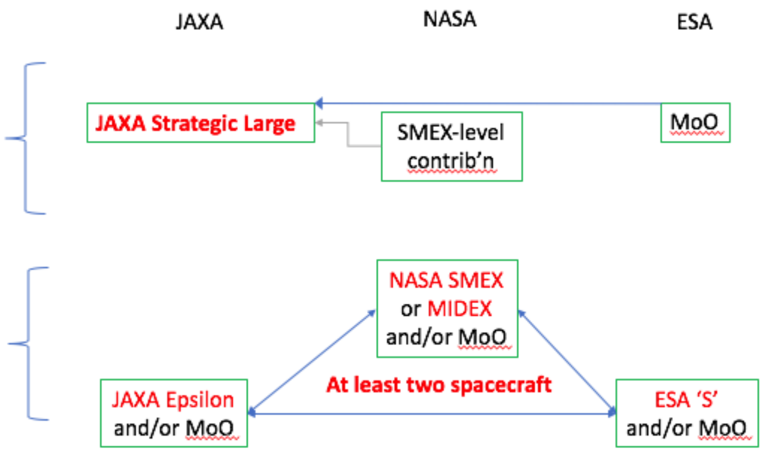


Figure 4-1: Possible configurations for collaborative NGSPM mission

A single-platform configuration of the type represented in the top row of Fig. 4-1 is the SOT's highest priority recommendation, for the following reasons. Organizationally and logistically, the multi-spacecraft configurations are the most challenging: delays in selection of instrument proposals, in construction/integration/ testing, and in launch of the spacecraft could easily result in the separate platforms being launched out of sync. Moreover, we find that the 1m diameter of the T-01/04/05 telescope can only be accommodated on a platform as large as the Strategic Large platform, so that any configuration which places the photospheric/chromospheric instruments on a smaller platform will necessitate T-02 instead of T-01/04/05.

In terms of the required combination of coronal/TR spectroscopy and imaging, and lower-atmospheric magnetometry, this large mission has evident similarities to the previously-proposed Solar-C mission. However, the largest telescope (T-04) has decreased in size, its focal plane package is less complex, and the launch cost has been reduced significantly. We can envision the international contributions being simpler and with cleaner interfaces.

If a single-platform configuration is not possible or available, another configuration which might be plausible is a constellation comprised of a NASA MIDEX (e.g., with T-07 and T-09) and a JAXA Epsilon (e.g., with T-02), with MoO contributions from ESA for portions of all three instruments. Alternatively, we can envision T-09 launched on a JAXA Epsilon, with contributions from the other agencies. Since T-09 alone is insufficient for the science objectives of NGSPM, this would have to be paired with either T-01/04/05 and T-07 on a JAXA Strategic Large, or T-02 and T-07 each to be launched on a SMEX/MIDEX or Epsilon. In this case, dedicated AOs would be strongly recommended in order to preserve the ability to include all the high-priority instruments in such a "distributed" NGSPM mission. Also, it will be crucial for the operational phases of the constellation spacecraft to overlap by at least two years. We stress that other possible configurations exist, and the agencies should pursue the arrangement that best fits within the resource constraints while preserving the multi-instrument combination (T-09, T-07 and T-01/04/05) that addresses the priority science objectives.

4.7. Possible additional instrument

As the next-highest priority instrument for elemental-scale science objectives, the addition of T-10 to our existing top 5 priority instruments would add significantly to capacities in coronal heating, reconnection, and flare science. T-10 is a high-energy (~0.5--50 keV) spectroscopic imager, emphasizing superhot and non-thermal bremsstrahlung emission produced in solar flares. Energy resolution of 100 eV at around 5 keV also allows diagnostics based on SXR emission lines in this range. To make significant advances it must have a low background - i.e. little scattered light - to allow simultaneous detection of bright chromospheric and faint coronal X-ray sources. This requirement pushes us towards precision grazing-incidence focussing X-ray optics (Wolter Type-I), which currently implies a FWHM of around 5”. Sub-second time resolution is required to capture the impulsive evolution of flare heating and acceleration, and a large field-of-view encompasses a large active region and its overlying coronal structures (~300”). Different channels and detectors, corresponding to different focussing optics modules, are employed for low and high energy ranges.

4.8. Recommendations

- We recommend that the science focus of NGSPM be the investigation of physical mechanisms on the smallest resolvable time- and length-scales relevant to the energetic or flux transfer processes, at all temperature domains in the solar atmosphere, as described in Section 3.3.2.

- We find that instruments with the capabilities represented by T-09, T-07, T-04, T-01, and T-05 are the highest priority for advancing the science objectives mentioned above within the next decade.

- We recommend that the NGSPM consist of the instruments listed above operating simultaneously, in full-Sun orbit(s), with sufficient telemetry coverage.

- We recommend that NGSPM be realized with a single platform, as a JAXA Strategic Large mission with contributions from NASA (SMEX-level), ESA (MoO), and ESA member states. If the single-platform approach is not possible or available, a combination of two or three spacecraft can achieve many of the NGSPM objectives, with some loss of capability and at increased risk.

- We recommend that the agencies form a unified Science Definition Team for NGSPM as soon as possible to define the agencies’ respective contributions in more detail.

- Given the current timing of upcoming proposal opportunities, we recommend that JAXA allow for the possibility of moving an instrument proposed for an Epsilon mission into a Strategic Large mission at a later time.

- Given the current timescale for M and L-class missions, we recommend that ESA support European contributions to NGSPM in the form of a Mission of Opportunity and/or an ‘S’ mission, depending on the approach taken to implement NGSPM by the agencies.

- We recommend that NASA support contributions by US scientists to all instruments of NGSPM. The NASA contribution to a JAXA Strategic Large mission should be at least the size of a SMEX mission. For a constellation configuration, the NASA contribution should be as large as a MIDEX, with possible contributions from other agencies, depending on the approach taken to implement NGSPM by the agencies.

- We recommend that NASA have a proposal opportunity dedicated to NGSPM, in either the single-platform or multi-spacecraft configuration, so that all 3 agencies can proceed with the mission in a coordinated and timely fashion.

- We recommend that in the longer term the international community coordinates to fill critical gaps in available vantage points, in order to obtain a global understanding of the Sun.

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Appendix A

Charter for the "Joint Next Generation Solar Physics Mission" Science Objectives Team

The joint Next Generation Solar Physics mission (NGSP) Science Objectives Team (SOT) is an advisory group for the study of a possible multilateral United States National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA), and European Space Agency (ESA) solar physics mission concept. NGSP will be a next-generation solar physics satellite concept to capitalize on the highly successful collaborations between NASA, JAXA, and ESA, including Yohkoh (Solar-A), Hinode (Solar-B), Geotail, Chromospheric Lyman-Alpha Spectro Polarimeter (CLASP) (sounding rocket), and Solar and Heliospheric Observatory (SOHO). The membership of this multi-lateral team is selected jointly by Institute of Space and Astronautical Science (ISAS)/JAXA, NASA, and ESA. The team reports their results to responsible personnel of all agencies.

The SOT is composed of scientific specialists who have been selected to represent the broad interests of the heliophysics research community. The primary role of the SOT is to develop and document scientific goals and priorities of a potential multilateral NGSP mission within the resources to be specified by the Agencies. Such mission would be subject to the normal proposal and peer review cycles of all the partners.

NGSP is likely to be a Japan-led mission expected to include substantial contributions from the United States and Europe. While a previous series of studies for a next generation solar physics investigation have been conducted over the past 5 years for a mission to launch in the 2019-2020 timeframe, the SOT study will investigate mission science requirements for a potential mission to be launched after 2024. The earlier studies will inform the SOT study. Progress in solar physics research and instrument technology, as well as changes in priorities and resources within the Agencies, are expected to change the scientific goals for the mission being studied for the new time frame. The SOT will identify and assess the science opportunities of the NGSP mission.

Specifically, the SOT will work closely with JAXA, the National Astronomical Observatory of Japan (NAOJ), ESA, and NASA to:

- Develop the scientific goals for NGSP, recognizing general limits on resources likely to be available for this activity.
- Assess how these scientific goals are aligned with JAXA, ESA and NASA agency priorities.
- Assess the required measurements necessary to meet the science goals.
- Assess the top-level observational (mission design) strategy for the NGSP mission to accomplish the scientific goals.
- Identify the minimum performance for the mission systems that is necessary and sufficient to justify the international investment into the merged project
- Deliver a science report that supports the generation of documents suitable for input into any future joint Announcement of Opportunity or Call for Missions. The draft of this report will be delivered to the participating agencies 9 months after the first meeting of the SOT, and the final report 12 months after the first meeting.

Once the SOT has delivered the final report, the team will be disbanded.

Appendix B

Science objectives for NGSPM

I: Formation mechanisms of the hot and dynamic outer solar atmosphere

I-1: Understand the formation mechanism of chromospheric fine scale dynamic structures and their influence in the corona

Background

The Sun is very dynamic as a result of the interaction of the solar magnetic field with the plasma of the solar atmosphere, from the photosphere to the corona. A crucial region for this interaction is the solar chromosphere, which is where the transition occurs from the plasma dominated lower atmosphere to the magnetic field dominated upper atmosphere. Understanding the structuring and dynamics of the chromosphere is important in itself but also in constraining the mass and energy loading processes that define the heating of the corona and the acceleration and composition of the solar wind.

Chromospheric structuring is intrinsically small-scale. There is a plethora of small and rapid chromospheric phenomena: fibrils, spicules, dark and bright mottles, mini- and micro-jets, Ellerman bombs and moustaches, UV-bursts, mini-flares and mini-CMEs, and more with similarly evocative names. With the theoretical understanding made possible by increasingly realistic, large-scale simulations, time is ripe to replace such traditional phenomenology by physical understanding in a coherent framework. Observationally, high spatial resolution is needed with full maps of both the velocity field and vector magnetic field at high temporal cadence.

Tasks

- I-1-1: Observe magnetic topology and dynamics at the foot point of chromospheric fine scale jets (eg. spicules) to see the discontinuity and shears of magnetic structure, and observe the interaction of magnetic field and convection by which these topologies are formed.
- I-1-2: Observe propagation of slow mode MHD waves and/or torsional Alfvén waves along the jets, and identify driving mechanism of jets and evaluate the heating in the chromosphere
- I-1-3: Observe the response of the corona above jets and identify the supplied mass and thermalization process

Key observations

- High spatial resolution (0.1"-0.3") of magnetic topology and dynamics for the photosphere and chromosphere with high cadence (10s or less) for a small FOV (>10") (I-1-1, I-1-2)
- Simultaneous imaging and spectroscopic measurements of transition-region and corona (0.01~5MK) with a similar spatial resolution (0.3") and cadence for a moderate FOV (>50") (I-1-3)

I-2: Test the nanoflare-heating hypothesis

Background

Coronal loops are seen as the basic structuring element of the solar outer atmosphere. In addition to warm (1MK) loops, active regions have hot (3 – 4 MK) loops, which are spatially unresolved by Hinode/XRT and SDO/AIA, probably because they are densely packed. Spectroscopic measurements in the EUV have suggested that only 10% of the volume of hot coronal loops is filled with plasma, when they are observed with a spatial resolution of 2″ − 3″ (Warren et al. 2008). Thus, measuring plasma parameters within the overall loop envelope and understanding the sub-structures is crucial for testing the nanoflare heating hypothesis.

A possible scenario is that these loops are heated by small-scale energy releases, often called nanoflares, occurring in the corona. Nanoflares may be a result of braiding and subsequent reconnection of magnetic field lines driven by magneto-convective forcing (Parker 1983). One important issue is to observationally identify the occurrence rate and energy size of heating events. If nanoflares occur in a loop with high enough frequency, the plasma properties will resemble that of steady heating, producing substantially isothermal emission at 2 – 3 MK. On the other hand, low-frequency nanoflares allow the loop to cool down before being reheated, which would result in a multi-temperature structure where faint emission at extremely high temperatures (≈ 7 – 10 MK) is also produced. This tenuous and very hot component has been inferred from Hinode/XRT data by various authors (e.g., Reale et al. 2009, Schmelz et al. 2009) but it is not confirmed by EIS spectroscopic data (e.g., Warren et al. 2011), the combined XRT and EIS observations (Testa et al., 2011; Winebarger et al. 2012), and FOXSI sounding rocket hard X-ray measurement (Ishikawa et al. 2014). Spectral lines such as the relatively strong and unblended Fe XVIII 974.86 Å line (7.1 MK) in UV/EUV (Teriaca et al. 2012) and the X-ray wavelengths for detecting plasma formed at even higher temperatures need to be used to quantitatively explore this hot component.

The frequency of the energy deposition is also expected to affect the time scales of flows and brightenings observed at the footpoints of the hot loops, in the so-called moss regions. The intensity of moss is very sensitive to changes in heating and the temporal evolution of the moss mimics the heating of the coronal loop. Up to now, spectral and imaging studies of moss have found a relatively small temporal variability that has often been interpreted as an indication of quasi-steady heating of the hot core loops (e.g., Brooks & Warren 2009). However, very high spatial resolution (~0.25”) observations by the Hi-C sounding rocket experiment showed a couple of braided field lines and the resulting reconnection and heating of plasma to very high temperatures (Cirtain et al. 2013) and revealed a higher variability on shorter time scales that seems consistent with impulsive heating (Testa et al. 2013).

The spatial distribution of the moss can be also used to infer how the heating depends on local magnetic field strength (Winebarger et al. 2008). Coronal imaging observations will be able to detect braiding in the corona, and UV spectroscopy with wide temperature coverage will allow full tracing of the thermal evolution of the coronal loops in response to any kind of braiding. A crucial measurement to establish whether magneto-convective forcing creates the braiding and subsequent reconnection of the magnetic fields in the corona is to relate heating phenomena to the magnetic field structures and their activities at the photosphere and chromosphere.

High sensitivity of the instruments will allow us to determine the frequency of energy release and distinguish between heating that is effectively steady and heating that is fully impulsive. In addition to making specific predictions of emission measure distributions, nanoflare models also predict line profile asymmetries and shifts requiring a high spectral resolution spectrograph for detection of the generation of high speed plasma expected from the magnetic reconnection. This is truly a discovery space, which likely holds the key to a wide variety of solar phenomena that involve the sudden release of magnetic energy. Besides its time scale, also the location of the heating along loops is a matter of debate as different spatial distributions are expected to give different observational signatures. Heating at the footpoints, for instance, is expected to lead to thermal instabilities that produce cool down-flowing plasma due to condensation. Recent observations show cool plasma blobs with widths ≥ 150 km falling along magnetic field lines over large part of active regions (Antolin et al. 2012). Spectroscopy with 200 km sampling over a wide range of temperatures will allow following the temporal evolution of the thermodynamical state of the great majority of these blobs providing insights on the heating mechanism.

Tasks

- I-2-1: Observationally identify the occurrence rate and energy scale of elementary heating processes with a sensitivity of 10^{22} erg
- I-2-2: Observe 10^7 K temperature plasmas and high velocity plasma motions in resolved coronal loops
- I-2-3: Full tracing of thermal evolution in coronal loops in response to any kind of braiding
- I-2-4: Establish whether magneto-convective forcing creates the braiding and subsequent reconnection of magnetic fields in the corona

Key observations

- High spatial resolution for measuring plasma parameters and identifying magnetic sub-structures within the overall loop envelope (I-2-1, I-2-2, I-2-3)
- Relatively strong and unblended UV spectral lines and/or X-ray measurements for exploring the hot (>5MK) plasma component (I-2-1, I-2-2)
- High cadence and high spatial resolution imaging for the temporal evolution of the moss at the coronal footpoints (I-2-1, I-2-2)
- High sensitivity, high cadence, and high resolution UV spectroscopy for wide temperature coverage (I-2-3)
- Simultaneous measurements of magnetic field structures and their activities at the lower atmosphere (I-2-4)

I-3: Test the Wave-heating hypothesis

Background

Despite significant progress in the past decade, the detailed nature of the processes that power the corona and solar wind remain poorly known. Waves, currents and reconnection may carry or release substantial energy, but it remains unclear how important each is for the local energy balance, how this depends on solar region, and how the conversion of non-thermal to thermal energy works in detail.

Recent observations have confirmed the presence of many different types of waves throughout the corona that may carry a substantial amount of energy [De Moortel & Nakariakov 2012]. Incompressible waves, e.g., Alfvénic waves, are suspected to be important in heating the corona [Matsumoto 2016] and driving the solar wind [McIntosh et al 2011], but it remains unclear what role they play, as the limited spatio-temporal resolution of current observations leaves wave heating models poorly constrained. The exact wave energy content is uncertain and direct observations of wave dissipation are elusive [McIntosh & De Pontieu 2012; De Moortel & Pascoe 2012; Hahn & Savin 2013]. Measuring the properties of both transverse and longitudinal waves in coronal holes can sample the footpoint regions of the solar wind and test recent models of wave dissipation [van Ballegooijen & Asgari-Targhi 2016]. These measurements will provide constraints to models of the origin of turbulence in the heliosphere. Off-limb line broadening will also constrain wave damping in the source regions of the fast solar wind.

Velocity and line broadening oscillations occur across coronal loops on spatial scales of 500 km and with the amplitudes (20-30 km/s) and periods (of 30-60 s) that are predicted by numerical models in which Alfvén waves generated in the photosphere propagate into the corona and dissipate to smaller scales through a turbulent cascade [van Ballegooijen et al 2011]. Current instrumentation (e.g., EIS) cannot resolve these predicted signatures and cannot properly constrain the models. Recent IRIS and SOT observations and modeling of prominence oscillations [Okamoto et al 2015, Antolin et al 2015] may have revealed resonant absorption for the first time. While dissipation occurs on scales that are smaller than can be directly observed, models suggest that the instability that leads to the cascade to smaller scales leaves tell-tale signatures that can be detected through phase relations between Doppler and line width and transverse motions of loops for various temperatures.

Tasks

- I-3-1: Determine the energy density of MHD waves as a function of height and frequency at chromospheric, transition region and coronal temperatures, in various solar environments including active region loops, coronal holes, quiet sun and prominences. Estimate the reflection at the TR and transmission to the corona of the various waves and shocks traveling upwards through the chromosphere. Determine the type of wave modes present in these structures and the nature of mode conversion that takes place.
- I-3-2: Identify the excitation mechanism of waves by observing the interaction of flux tubes and convection, magnetic reconnection in the lower atmosphere.
- I-3-3: Observe discontinuous structures of physical quantities in the chromosphere and corona as a signature of non-linearization processes (shocks). Identify locations and mechanisms of dissipation (by comparison with models), along with direct evidence for heating and estimates of the energy made available for thermalization. Compare the energy dissipation with heating requirements in the different environments. Observe the dynamical effects (e.g., acceleration of steady flows or jets) that may result.

Key observations

- Measure time-series of line profiles (with enough spectral resolution to estimate line widths and asymmetries) at different heights in the photosphere/chromosphere/ corona, with sub-arcsec resolution in different regions (AR, QS, CH, prominences); spatial coverage must be large enough to allow simultaneous measurements over entire AR loops, prominences, plumes, etc. (I-3-1, I-3-2, I-3-3)
- Simultaneously collect images with similar or higher spatial resolution for measuring motions in the plane of the sky in the same temperature ranges (I-3-1, I-3-2, I-3-3)
- Measure phase relations between the observables as functions of frequency and height (I-3-1, I-3-2)
- Measure correlations between incident wave amplitudes and heating or dynamical events (I-3-3)

I-4: Understand the role of magnetic flux emergence in the heating of the chromosphere, transition region and corona

Background

Magnetic flux emergence is a ubiquitous process in the solar surface. It occurs on all spatial scales accessible to current instrumentation, from the tens of thousand km of large active regions down to the 100 km of the tiniest magnetic flux concentrations observed in the quiet Sun. High spatial resolution and high sensitivity polarimetric measurements have revealed enormous flux appearance rates, particularly in the solar internetwork. While active regions bring flux at a rate of about 0.1 Mx cm^{-2} day^{-1} during the maximum of the solar cycle (Schrijver & Harvey 1994), magnetic flux appears in the internetwork at rates that are three to four orders of magnitude larger, independently of the solar cycle (e.g., Zirin 1987; Thornton & Parnell 2010; Gosic et al. 2016; Anusha et al. 2016). Thus, the internetwork supplies nearly all of the flux emerging on the solar surface. Also, internetwork regions are present everywhere, from the poles to the equator. This has led to the idea that flux emergence in the quiet Sun may be a crucial mechanism for chromospheric and coronal heating.

Support for this scenario is provided by the observation that about one quarter of the bipolar flux structures emerging in the internetwork rise to the chromosphere, carrying magnetic energy with them (Martinez González & Bellot Rubio 2009; Gömöry et al. 2010; Martínez González et al. 2010). The resulting energy flow turns out to be of order 10^6-10^7 erg cm^{-2} s^{-1} (Ishikawa & Tsuneta 2009; Martínez González et al. 2010), which is nearly sufficient to balance radiative losses in the chromosphere (Anderson & Athay 1989). The actual energy flow could be even larger, due to the limited sensitivity and short time sequences that can be achieved with current instruments.

However, we still do not know how the energy carried by the loops is released in the chromosphere and perhaps also in the transition region and corona. The most obvious candidate is magnetic reconnection. Reconnection can happen during the ascent of the loops and through cancellation with pre-existing magnetic patches of opposite polarity, but only glimpses of those processes and their effects on the chromosphere, transition region, and corona have been observed so far (e.g. Guglielmino et al. 2009; Ortiz et al. 2010; Ortiz et al. 2016). Rising loops may also generate waves and channel photospheric oscillations, whose energy would then be dissipated in higher layers. These mechanisms provide additional ways to heat the solar atmosphere, but need to be confirmed observationally.

To assess the role of emerging flux in chromospheric and coronal heating, it is necessary to determine the exact amount of magnetic flux that is actually emerging in the solar photosphere on all spatial scales (both in active and quiet regions), to characterize the processes whereby they transport magnetic energy and magnetic helicity to the chromosphere and above, and to understand how their magnetic energy is released there. This requires high-sensitivity observations covering all the layers of the solar atmosphere at similar spatial and temporal resolution for long periods of time. In order to demonstrate the existence of magnetic reconnection, it is important to measure magnetic fields not only in the photosphere but also in the chromosphere and transition region. Obtaining long duration sequences of such measurements is not possible from the ground, due to the image degradation induced by atmospheric seeing and the complete absorption of UV and EUV radiation in the Earth's atmosphere.

This investigation will also help solve an intriguing aspect of solar magnetism, namely how magnetic flux disappears from the internetwork. So far, three mechanisms have been identified: fading, flux transfer to the network, and flux cancellation (Gosic et al. 2016). Interactions between mature network and internetwork elements are likely to result in increased cancellation of opposite polarity patches and magnetic reconnection, providing additional opportunities for atmospheric heating. Thus, another important goal is to determine accurate flux cancellation rates in the quiet Sun and study their influence in all layers of the solar atmosphere.

Tasks

- I-4-1: Determine the topology of emerging/cancelling magnetic flux in the photosphere and chromosphere on small and large spatial scales
- I-4-2: Determine flux emergence/cancellation rates as a function of flux content in the quiet Sun and active regions, improving the current detection limit by at least one order of magnitude
- I-4-3: Characterize processes through which the energy carried by emerging magnetic flux is transferred to and released in the chromosphere, transition region, and corona. Determine the fraction of total magnetic energy dissipated in the upper atmosphere

Key observations

- Simultaneous observations in visible, UV and EUV to study ascent of emerging flux throughout the solar atmosphere with matching spatial resolution and cadence (I-4-3)
- Spectropolarimetry in photospheric and chromospheric lines to infer magnetic topology of emerging flux, preexisting fields, and interactions between them (I-4-1, I-4-2, I-4-3)
- High polarimetric sensitivity (10^{-3}-10^{-4}) to detect the weakest quiet Sun magnetic features (I-4-1, I-4-2, I-4-3)
- Spectroscopic and imaging observations in transition region and corona to study consequences of flux emergence in upper atmosphere (I-4-3)
- High spatial resolution to detect small internetwork flux concentrations and magnetic reconnection (I-4-1, I-4-2, I-4-3)
- Large field of view to cover several supergranular cells and study evolution of flux emerging in the cell interiors and cancellations with network elements (I-4-2, I-4-3)
- High cadence (~30 s) to study emergence and cancellation events (I-4-1, I-4-2, I-4-3)
- Long, uninterrupted time sequences (2-5 days) to cover lifetime of supergranular cells and formation/decay of active regions (I-4-2)

I-5: The Sources and Driving Mechanisms of the Solar Wind

Background

The solar wind carries a kinetic energy larger than the energy X-ray radiation of the solar corona, and it directly affects the Earth. It is intimately related to the solar dynamo, since it varies with the solar cycle, it is driven by magnetic forces, and it may play an active role in shedding magnetic helicity. The solar wind is divided into fast and slow streams. Not only do the speeds differ by nearly a factor of 2, but the temperatures, ionization states and elemental compositions are also different.

Three fundamental questions about the wind are 1) to what extent is it heated and driven by MHD waves versus magnetic reconnection, 2) what role do jets and spicules play in injecting mass and energy into the wind, and 3) how does the geometry of the magnetic field affect the wind parameters? To answer these questions we need to determine the sources of the wind streams and to measure signatures of the basic physical processes.

The sources can be found by comparing the ionization temperatures and elemental compositions measured in situ with those observed remotely above the solar surface and in the region where the wind accelerates. To first order, the high ionization temperatures and strong First Ionization Potential (FIP) effect in the slow wind match those seen near streamers, while the low T_i and weak FIP bias of the fast wind match coronal holes. It should be possible to trace specific parcels of gas back to their solar origins by tracing the flow backwards in global MHD, though in practice this is tricky, especially near solar maximum. More detailed study shows short time scale dropouts of heavy elements matching the low abundances seen in the closed field regions of quiescent streamers, and models show that the ionization state, which is given the product of density and flow time at the coronal temperature in the MHD models, does not match that measured at 1 AU. Other outstanding problems include the roles of the S-web of open quasi-separatrix field lines and injection of plasma confined in loops by reconnection between open and closed field lines.

To answer those questions we need better models of the magnetic field structure and plasma parameters on small scales along with sensitive UV spectroscopy and high cadence EUV images to determine abundances and ionization states between the solar surface and about 5 R_{SUN}, along with white light coronagraph images for the overall morphology. The geometry of magnetic flux tubes also controls the adiabatic cooling of flows and determines the final speed of solar winds.

By examining the temporal variation of Alfvénic Poynting flux and hydrodynamical acoustic flux with height we can estimate the heating rate by the dissipation of Alfvénic waves and by shock waves. The dissipation of Alfvénic waves is led by cascading MHD turbulence and nonlinear generation of compressive waves: the latter process eventually triggers the heating by shock dissipation. The heating process can also be studied by measuring the preferential heating of heavy ions as a function of charge-to-mass ratio. The preferential heating is usually interpreted as a signature of resonant heating by Alfvénic waves from turbulent cascade, but shock waves have also been suggested. UV spectroscopy with a substantial wavelength range and the sensitivity to cover the lines of many elements and to obtain high temporal resolution is the key requirement, along with EUV and white light images and high resolution magnetograph data to specify the lower boundary conditions. Instrument parameters depend on the region being observed, but ~ 30 km/s resolution, ~ 30 second cadence and a large portion of the 500 - 1500Å range are desirable.

Tasks

- I-5-1: Observe magnetic fields in the photosphere and chromosphere in coronal holes that initiate the solar wind and determine the geometry of flux tubes connecting to the corona.
- I-5-2: Determine the large scale configuration of coronal magnetic field
- I-5-3: Determine the mass and energy fluxes injected by spicules (low heights) and jets (larger heights) in coronal holes, quiet regions and active regions from intensity changes in lines covering a broad range of temperature
- I-5-4: Determine the mass fractionation in coronal base and identify the source regions of the solar wind measured in interplanetary space by comparing the abundances of different FIP elements
- I-5-5: Determine the radial profiles of solar wind acceleration and the spatial distribution of the driving force
- I-5-6: Determine the properties of compressive waves from intensity changes and of Alfvén waves from velocity shifts as functions of height and measure their energy fluxes as a function of height, and identify wave reflection, cascade and turbulence
- I-5-7: Identify the evidence of resonant heating by determining the preferential heating at larger heights where the plasma is collisionless for several ions with a range of charge to mass ratios from line widths with higher sensitivity (spatial and temporal resolution)
- I-5-8: Provide context observations of plasma parameters in the solar wind acceleration region up to 5 solar radii to enhance the in situ measurements of particle distributions and wave properties by Solar Orbiter and Solar Probe Plus beyond 10 solar radii. Spectra must be obtained off limb below the trajectory of the in situ probes.

Key observations

- High-sensitivity spectropolarimetry of photospheric, chromospheric, and coronal lines (I-5-1, 1-5-2)
- Stereoscopic imaging and spectroscopy (I-5-2, 1-5-5, I-5-7)
- Sensitive UV spectroscopy (suggested range: 500-1650A) with 30 km/s resolution and high cadence (~30 sec) for examining temporal variability, line widths and line intensities as signatures of driving mechanisms. (I-5-3, I-5-6)
- High-sensitivity coronal spectroscopy for Lyman lines and lines of different FIP elements (I-5-4, 1-5-5)
- Sensitive white light coronal and heliospheric images to obtain morphology and average electron density. (I-5-2, I-5-5, I-5-6)
- Observe coronal holes, quiet regions and active regions off-limb to obtain plasma parameters as functions of height. (I-5-1, I-5-4, I-5-8)

- In-situ measurements for comparison to source regions, provided by Parker Solar Probe and Solar Orbiter. Measure the degree of preferential heating of elements of different charge-to-mass ratios from the widths of lines of several ions, including He^{+}. (I-5-4, I-5-7,1-5-8)

I-6: Formation mechanism of prominence

Background

Solar prominences (dark filaments as seen on the solar disk) are relatively cool (T ~ 10^4 K) and dense (n ~ $10^{11\sim12}$ cm^{-3}) plasma suspended in surrounding hot corona above magnetic polarity inversion lines on the solar surface. They are one of the most conspicuous ingredients of the solar atmosphere with the size of up to the solar diameter and the life time longer than weeks. Prominences occasionally suffer a sudden destabilization followed by a dynamic eruption, which is often associated with a flare and CME that yield a significant impact on the space environments of the Earth. Recent high resolution imaging observations have revealed that prominences consist of sub-arcsecond fine scale elongated structures and they are highly dynamic exhibiting oscillations (Okamoto et al. 2007), convections (Berger et al. 2010), persistent flows and turbulences (Hillier 2016). The prominence is thus a particularly interesting object in regard to the fundamental MHD processes of partially ionized plasma and the mechanism of the solar explosions. Major questions on the prominence are as follows:

1. What is the magnetic field structure that supports the prominence plasma?
The magnetic field configuration of prominences is still under debate especially for quiescent type prominences, which is dominated by vertically elongated structures showing convective motions. Erupting prominences often reveal a hint of helical structures, and direct measurements of magnetic helicity or electric currents in prominences is of a particular importance to evaluate the stored magnetic energy and to understand the mechanism of the eruptions and flares.

2. How is the prominence plasma supplied?
Two major scenarios are under debate, i.e., direct injection of chromospheric material through magnetic reconnections or flux emergence, and condensation of the coronal hot plasma by thermal instability. To understand the origin of prominence material in view of the mass circulation in the solar atmosphere is one of the most important parts of understanding the formation mechanism of the hot and dynamic outer solar atmosphere.

3. What causes the sudden destabilization and eruption of the prominence?
The mechanism that initiates the instability of the prominence structure is still unclear. Two scenarios are considered, i.e., self-destabilization, in which the magnetic structure of the prominence loses the stable condition according to gradual change of the magnetic boundary condition due to photospheric plasma flows, and externally triggered destabilization caused by magnetic reconnections between a part of the prominence and surroundings such as the emerging flux, adjacent flux loop and overlaying magnetic fields. This question is described in topics II-2 and II-3.

Tasks

Understanding of the prominence is thus closely related to the understanding of the flare, CME and the coronal heating mechanism. The following observational tasks are crucial to solve these problems;

- I-6-1: Measure the magnetic field structure that supports prominences
- I-6-2: Detect mass circulation among chromosphere – prominence – corona
- I-6-3: Track the time evolution of photospheric and chromospheric magnetic fields near neutral lines, and clarify the condition of formation and destabilization of prominences.

Key observations

- High precision spectro-polarimetry (accuracy 10^{-4}) of prominence lines with spatial resolution 0.4" for FOV > 200" (I-6-1, I-6-3)
- High resolution spectro-polarimetry (accuracy 10^{-4}) of photospheric lines with spatial resolution 0.2" for FOV > 200" (I-6-1, I-6-3)
- High resolution images and velocity and magnetic fields in wide range of temperature ($6x10^3 \sim 2$ x 10^6K) with high spatial resolution (0.3" or higher) for FOV > 300", and for continuous observations over several days (I-6-2, 1-6-3)

II：Mechanisms of large-scale solar eruptions and foundations for prediction

II-1: Measure the energy build-up processes in flaring and CME regions

Background

Solar flares and coronal mass ejections (CMEs) originate from regions with complex, dynamic magnetic field configurations. These fields exhibit pronounced non-potentiality of the coronal field reflecting the presence of free energy, i.e., energy in excess of the potential field energy that sets a maximum to the energy available to power one or more flares or CMEs from the region. The energy buildup occurs either below the surface, which is then transported to the solar atmosphere via interaction of emerging flux with the pre-existing field, or within the solar atmosphere itself. Quantifying the degree of non-potentiality of, or measuring the amount of free energy contained within, a region that subsequently erupts is a key towards comprehensive understanding of flares/CMEs and is indispensable for space weather forecast research.

There are basically the following two ways to quantify the free magnetic energy in the solar corona.

1. The free energy can be quantified by a three-dimensional magnetic field model reconstructed from vector magnetic field observed on the solar surface and solving the boundary-value problem of MHD equilibrium. The nonlinear force-free field (NLFFF) extrapolation from the vector magnetic field measured on the photosphere is then applied. However, a problem of this method is that the photospheric magnetic field is usually not consistent with a force-free (magnetically-dominated) field (Metcalf et al. 1995). Several methods to overcome the problem have been proposed. One is to measure the magnetic field vector at the upper chromospheric boundary where the plasma beta (the ratio of plasma pressure to magnetic pressure) is relatively low and the magnetic field is more force-free than the photosphere. Another approach is to develop new MHD equilibrium models that explicitly take plasma pressure and gravity into account. Observations of coronal loops or prominence morphologies, or spectropolarimetric observations of prominence/corona magnetic fields (e.g., Lin et al., 2000; 2004; Bak-Steslicka et al. 2013; Rachmeler et al. 2014; Lopez-Ariste, 2015) can provide further constraints. These may be directly incorporated into boundary-value coronal models (e.g., Savcheva & van Ballegooijen, 2009; Malanushenko et al., 2014; Dalmasse et al., 2016), or be used along with the boundary condition in reconstructing the coronal magnetic field through stereoscopic/tomographic methods (e.g. Kramar et al. 2014).

2. For active regions (ARs) the variation of magnetic free energy can be inferred by the measurement of Poynting flux on the photosphere. In order to do it, we need to know the velocity vector as well as the magnetic field vector at the photosphere as a function of position and time. Local correlation tracking and the inversion of the induction equation can be used to derive the velocity on the

photosphere from the evolution of magnetic field. However, the reliability of this method for the measurement of magnetic free energy is not yet confirmed quantitatively.

Tasks

- II-1-1: Determine the magnetic field configuration and magnetic free energy stored in the corona using models based on measurements of the photospheric and chromospheric magnetic boundary, and study its time evolution.
- II-1-2: Measure the Poynting flux on the photosphere and identify the mechanism that carries the magnetic free energy into the corona.
- II-1-3: Measure the development of the magnetic structure of dark filaments (prominences on the limb), in the time leading up to eruption.
- II-1-4: Use intensity and polarimetry measurements to constrain coronal magnetic field models of eruptive regions.

Key observations

- Stable and continuous measurement of vector magnetic fields in photosphere and chromosphere for more than several days (II-1-1, II-1-2)
- Stereoscopic magnetograph measurements for resolving ambiguity (II-1-1, II-1-2, II--I-3, II-1-4)
- Velocity measurements in the photosphere (II-1-2)
- Vector magnetic fields and spectroscopy of dark filament (II-1-3)
- Coronal intensity and polarimetric measurements (II-1-4)
- Wide FOV covering AR or eruptive prominence (II-1-1, II-1-2, II-1-3, II-1-4)
- Data storage of large number of ARs (II-1-1, II-1-2)

II-2: Identify the trigger mechanism of solar flares and CMEs and distinguish between the many CME models

Background

In order to accurately predict when, where, and how space weather events are initiated, we must understand the interrelationship between small-scale processes, such as photospheric flux emergence and magnetic reconnection, and large-scale magnetic topologies, such as quadrupolar fields in the breakout model, or a magnetic flux rope structure. For example, flux emergence may drive changes in magnetic topologies that result in flare and CME initiation. Observations indicate that many flares are related to newly emerging flux and its interaction with pre-existing fields, and the higher the complexity and shear of the field the greater the chance of flares occurring. Some numerical simulations suggest that small magnetic flux emergences near magnetic polarity inversion lines may trigger the onset of solar eruptions. Alternatively, reconfigurations of the coronal magnetic field on global scales may lead to reconnections that trigger "sympathetic" eruptions. Measurements of magnetic fields and mass flows in the solar atmosphere (including chromosphere and corona) will provide new observational insights into flare and CME initiation.

Tasks

- II-2-1: High-cadence observation of plasma motions and fine magnetic structures interacting with surrounding fields in the chromosphere before flare occurrence
- II-2-2: Observe sudden reconfigurations of coronal magnetic field structures just before flare occurrence
- II-2-3: Observe dynamical changes of electric current system during eruptions.

Key observations

- Vector magnetic and velocity fields in photosphere and chromosphere at high-cadence (II-2-1, II-2-3)
- Spectroscopy of chromospheric/TR/coronal structures (II-2-1, II-2-2, II-2-3)
- Coronal imaging and polarimetry (II-2-2, II-2-3)
- FOV covering AR (II-2-1, II-2-3)
- Data storage of large number of events (II-2-1)

II-3: Understand the evolution and propagation of CMEs and their effect on the surrounding corona

Background

The driving mechanism of solar eruptions may be understood as a nonlinear feedback cycle between magnetic reconnection and MHD instabilities. Because the time scale of the impulsive phase of solar eruptions is as short as the Alfven time-scale, some kind of ideal MHD instability is thought to be involved. In particular, the kink and torus instability modes have both been suggested as being fundamental to the eruption. However, which mode of instabilities are responsible for the impulsive and eruptive phases, and what determines the acceleration profile of the CME, is still controversial.

It is generally agreed that what leaves the corona and travels through interplanetary space is often a magnetic flux rope (Vourlidas et al., 2013; and references therein). However, observations and models indicate that the magnetic structure that leaves the corona may bear little resemblance to the original erupting structure because it may reconnect with surrounding fields and/or rotate during eruption (Gibson and Fan, 2008; Shiota et al., 2010). In addition, deflection, distortion, and shock formation are all likely contributers to the evolution of the CME as it moves through the corona and inner heliosphere (e.g., Demoulin, 2008; Savani et al 2010; 2011; Isavnin et al 2014).

In order to determine how the CME evolves and propagates during its eruption, we have to carefully measure the evolution of the three-dimensional structure of the flux rope. Interactions with the ambient corona as manifested in dimmings, EUV waves, and shocks may provide clues to this evolution. In addition, if we can reconstruct a reliable three-dimensional coronal magnetic field in the pre-eruptive state (see II-1), a stability analysis might help us to infer the structure of growing mode.

Tasks

- II-3-1: Observe kinematics including rotation, acceleration, and interactions of CMEs
- II-3-2: Observe reconnection during the eruption
- II-3-3: Identify shocks and other waves associated with CMEs

Key observations

- EUV, white light coronagraph images with global FOV. (II-3-1: stereo; II-3-2, II-3-3)
- Heliospheric images (II-3-1 stereo; II-3-3)
- UV spectro coronagraph Doppler and line broadening (II-3-1; II-3-3)
- High resolution/high time cadence images in EUV, SXR, with large enough FOV to capture eruption interactions, reconnections, shocks, waves (III-3-1, III-3-2, III-3-3)
- HXR observations (II-3-2)
- Doppler observations of erupting prominence (II-3-1)

II-4: Understand the Processes of Fast Magnetic Reconnection

Background

It is generally accepted that magnetic reconnection is responsible for the initiation and the dynamical progression of coronal mass ejections (CMEs) and eruptive flares, both of which are primary drivers of heliospheric disturbances. As the central component in the two-dimensional framework due to Carmichael (1964), Sturrock (1968), Hirayama (1974), and Kopp and Pneuman (1976), often called the CSHKP model, reconnection forms the organizing element of much CME/flare research.

In a commonly invoked version of the CSHKP framework, a closed flux rope or *plasmoid* moves upward as its magnetic connections to the Sun are eliminated by reconnection at a magnetic X-point. Inflow sweeps magnetic field from either side into the X-point; outflow ejects newly closed field upward into the plasmoid and downward into a coronal arcade. As the reconnection progresses the X-point moves higher and its footpoints appear to spread apart. Images of post-eruption arcades and the spreading "ribbons" of the footpoints corroborate the model's overall geometry, including the cusp-like appearance of the most recently closed flux (Tsuneta, 1996) whose apex would lie somewhat below the X-point. Though the X-point itself is not directly observable, due to a lack of sufficient emission measure, the reconnection process is inferred by a wealth of detectable signatures across the electromagnetic spectrum (McKenzie, 2002).

However, the fundamental problem with scenarios invoking reconnection for, e.g., solar flares is that the expected rates of magnetic diffusion through the highly ionized coronal plasma are much too slow to account for the observed energy release. For although observations imply reconnection occurring on timescales of seconds or minutes, the electrical conductivity of coronal plasma, and the length scales of typical coronal features, tend to predict timescales that are several orders of magnitude longer. Thus the focus of this science objective is understanding, "What allows reconnection to proceed? How does it get accelerated?"

The localized conditions and dynamic processes within the plasma – especially in the *current sheet* defined by oppositely directed magnetic field – are critical for initiating, accelerating, and prolonging the reconnection; and yet despite the key role the local conditions play for reconnection, much is unknown about the dynamic physical processes in this region due to the small length- and time-scales pertaining to the variations, in addition to the aforementioned poor visibility of the X-point.

To understand the role played by reconnection in driving coronal activity we must quantify its effects and understand how they are related. Magnetic reconnection changes the topology of magnetic field lines, while converting magnetic energy into other forms of energy such as heat and bulk kinetic energy. Flows of magnetic field into and out of the reconnection site, and the conversion of magnetic energy to heat and kinetic energy, have not been quantitatively measured with adequate precision. Even as the X-point moves up the newly closed field lines should move downwards to dipolarize after reconnecting. Supra-arcade downflows (SADs) are downward-moving features observed in the plasma sheet, and are interpreted as direct evidence of the sunward outflows from highly localized ("patchy") reconnection within the current sheet. Analysis of the characteristics of these flows has yielded a windfall of information about current sheet reconnection, knowledge which may not be achievable by other means: e.g., no other direct signatures of, say, the spatial distribution of outflows are known. And while the presence of shocks in the reconnecting structures has been anticipated (Hara et al., 2011; Takasao et al. 2012), there is a lack of unambiguous observations. In non-flaring times – the prevailing condition most of the time – flux transfer between neighboring domains within an active region, or between distinct active regions, provides a crucial laboratory in which to identify and precisely measure reconnection episodes (e.g., Longcope et al. 2005).

Fundamental questions concerning magnetic reconnection in the corona include the following. How does the rate of reconnection compare to the rate of its driving from the photosphere? (II-4-2)

Does the relationship between topological change and energy dissipation depend on the amount of current accumulated during the pre-reconnection phase, as theoretical models predict? (II-4-2) What is the distribution of flux tube diameters, and fluxes, created by the reconnection process? What is the length scale and spatial distribution of diffusion zones within current sheets? (II-4-1, II-4-2) Do these distributions and length scales vary between different events or is it a fundamental characteristic of coronal reconnection? Is the reconnection patchy & discrete (cf. Longcope et al. 2005) or smooth and continuous (cf. Guo et al. 2014)? Are there shocks in the reconnecting structures, and if so then what are the properties of the shocks? (II-4-3)

Tasks

- II-4-1: Observe discontinuity of chromospheric magnetic fields (current sheets)
- II-4-2: Clarify key parameters that determine the reconnection rate; length scale of current sheet, strength of the guide field, forcing by ambient gas flows, plasmoid ejections
- II-4-3: Observe structures in density, temperature and velocity associated with coronal magnetic reconnection and verify relations of shock waves and plasma heating

Key observations

- Active region evolution: Detect all new connections in relation to flux emergence or in relation to current buildup within/between domains. Measure amount of flux transferred by reconnection; size (diameter) and flux density in each new flux tube; amount of heat energy deposited in corona; temperature & density within each new flux tube
- Flare current sheets: height and especially thickness of current sheet; spatial variation of density/temperature/thickness/nonthermal broadening within current sheet; inflow/ outflow from diffusion sites
- High-res and high-sensitivity coronal imagery, EUV and/or SXR, 0.5"/pix or better, 60s cadence uninterrupted.
- Coronal spectroscopy to match, EUV+SXR, also uninterrupted, for energetics, Doppler, nonthermal broadening
- Magnetic fields in chromosphere. (Being more nearly force-free, the chromospheric field provides a more reliable boundary condition for extrapolations into the corona.) 30min cadence
- Uninterrupted for ~3 days at a time (duration of AR emergence, or buildup time to flare)

II-5: Understand the formation mechanism of sunspots, in particular delta sunspots

Background

Formation and evolution of sunspots is one of the most fascinating phenomena on the Sun. Sunspots are the sites of energy-releasing events of various scales such as flares, coronal mass ejections (CMEs), jets, and brightenings in many different wavelengths. It has long been known that the most complex sunspot groups called delta spots, in which umbrae of positive and negative polarities share a common penumbra (Kuenzel 1960), produce larger flares (Sammis et al. 2000) and even solar particle events (Warwick 1966). Therefore, not only from the viewpoint of solar physics but also from that of the practical space-weather research, understanding of the formation of sunspots, especially of the most complex ones, is crucially important.

It is widely believed that sunspots are created through the emergence of magnetic flux from the convection zone (Parker 1955). Because direct optical observation of the interior is almost impossible, numerical approaches have been adopted to investigate the flux emergence (see reviews by Fan 2009, Cheung & Isobe 2014). In the present understanding, the emergence of magnetic fields is caused by the coupling of magnetic buoyancy and convective action (Nelson et al. 2011), a strong enough field is needed to successfully rise to the surface (Jouve & Brun 2009, Weber et al. 2011), and the observed asymmetries between leading and following polarities are the result of Coriolis force and large-scale convection (Fan et al. 1993). The combination of numerical simulations of rising magnetic flux and observations of surface flows places constraints on the subsurface rise speed of omega loops (Birch et al. 2016).

It has been proposed that helioseismology may be used to directly detect the subsurface magnetic field and associated flows. However this has proved very difficult for individual active regions. The way forward is to develop more reliable methods of helioseismic inference (to reduce biases), in combination with statistical studies of many hundreds of emerging active regions (to beat down random noise).

Various complex, fine-scale structures exist in sunspot regions (see reviews by Solanki 2003, Rempel & Schlichenmaier 2011, Borrero & Ichimoto 2011). Most of them are coupled with local convection and some are accompanied by dynamic activity events. For example, Hinode/SOT has discovered small-scale jet-like features in sunspot penumbrae (1000-4000 km; Katsukawa et al. 2007) and repeated bursty ejections from light bridges (1500-3000 km; Shimizu et al. 2009). Coordinated observations with IRIS and ground-based high-resolution telescopes (~0.06" for SST) make it possible to obtain thermal and velocity diagnostics in the chromosphere and transition region above the sites of such events and their detailed photospheric morphologies (e.g., Toriumi et al. 2015a,b, Vissers et al. 2015). Chromopsheric (vector) magnetic measurements may help understand not only the above-mentioned features but also the formation mechanism of the sunspot penumbrae (Shimizu et al. 2012).

One of the most prominent characteristics in the evolution of delta sunspots is the formation of strong-field, high-gradient, highly-sheared polarity inversion lines (PILs; e.g., Schrijver 2007). They indicate the existence of strong electric currents that can store free magnetic energy in the corona. Many authors have pointed out the importance of sunspot motions in the formation of such structures (Zirin & Liggett 1987, Tanaka 1991), which includes the emergence of a twisted flux tube and a resultant sunspot rotation (Leka et al. 1996, Kubo et al. 2007), interaction between a newly emerging bipole and a pre-existing spot (Kleint et al. 2015), and collision of two emerging bipoles (Chintzoglou & Zhang 2013). Therefore, a long-term (days to weeks) monitoring of photospheric vector magnetic fields in a developing delta sunspot region with a wide enough field-of-view (a few times 100") is necessary for understanding the formation process of sheared PIL, the possible location of future flare eruptions, and the large-scale supply of Poynting flux and current helicity. The obtained vector magnetograms may also be utilized in reproducing the coronal magnetic fields with non-linear force-free field extrapolation (NLFFF) techniques (see reviews by Wiegelmann & Sakurai 2012, Inoue 2016) or compared with numerical modeling of delta sunspots (e.g., Toriumi et al. 2014, Fang & Fan 2015, Takasao et al. 2015). Stereoscopic observations, which would be realized by Solar Orbiter, Paker Solar Probe, and L5-missions, may provide excellent opportunities to continuously monitor the delta-sunspots over the whole life cycle.

Above the sheared PIL in delta sunspots, arcade fields gradually produce a twisted flux rope, which is possibly due to the footpoint motion in the photosphere (van Ballegooijen & Martens 1989). This should be investigated by the simultaneous photospheric and chromospheric magnetic measurements. In addition, surrounding and overlying coronal fields, which determines whether the flare becomes CME-eruptive or not (Sun et al. 2015), should be investigated by EUV and X-ray observations.

Tasks

- II-5-1: Observationally reveal the origin and subsurface evolution of sunspot magnetic fields

- II-5-2: Investigate the coupling of small-scale magnetic fields and local convection and the resultant energy-releasing events
- II-5-3: Trace the formation process of sheared PILs and current-carrying coronal fields above

Key observations

- Long-term and wide-field-of-view monitoring of photospheric vector magnetic fields (II-5-2, II-5-3)
- Simultaneous high-resolution imaging spectropolarimetry in the photosphere and chromosphere (II-5-2, II-5-3)
- Local helioseismology and reconstruction of three-dimensional subsurface velocity and magnetic fields (II-5-1)
- Multi-wavelength (EUV and X-ray) monitoring of coronal magnetic fields (II-5-3)

II-6: Understand particle acceleration and flare energy transport

Background

The energy for a solar flare is generally understood to be stored in stressed magnetic fields in the solar corona. The flare energy, on the other hand, is mostly radiated by the chromosphere, with only a relatively small fraction radiated by the corona. Therefore, a substantial fraction of the flare energy must be transported from the corona to the chromosphere. Aspects of the transport process are intimately related to the problem of particle acceleration (electrons, protons, alphas and other heavy ions), since one possible mode of energy transport is by charged particle beams. However, at different phases of the flare, energy transport by (M)HD waves, or by thermal conduction may be relevant. Observationally, it is clear that non-thermal particles have a crucial role in a flare, with up to 50% of the stored magnetic energy estimated to be converted to the KE of non-thermal electrons and ions, present in both the chromosphere and the corona.

The most widely-accepted model for solar flare energy transport links the energy transport directly to the acceleration of electrons, in as much as the stored magnetic energy in the corona is converted *in situ* to the kinetic energy of non-thermal charged particles which then stream along closed magnetic field to the lower atmosphere where they deposit their energy collisionally, or along open field to the heliosphere where they are responsible for the generation of radio emission. The top-level questions to answer here are:

- How and where is magnetic energy converted into particle non-thermal kinetic energy (i.e. how are particles accelerated, what is the relationship to field reconfiguration including in the reconnection region)?
- How do those accelerated particles propagate through the magnetised solar plasma?

Magnetic energy can also be transported through the atmosphere by magnetic disturbances. For example an impulsive reconfiguration of the magnetic field, e.g. by magnetic reconnection, can launch a pulse of Alfven waves which are strongly ducted along the magnetic field to remote locations, where the wave energy is dissipated and converted into heat, particle KE and radiation. Relevant top-level questions here are:

- How are propagating magnetic disturbances generated in a flare reconfiguration?
- What happens to such disturbances as they propagate through the corona towards the chromosphere and into space?
- How and where is wave energy converted into particle non-thermal kinetic energy and/or heating?

While the flare impulsive phase is characterised by rapid timescales and non-thermal particles, these are not found at all sites in the chromosphere where flare excitation takes place, and are also absent (or present at a much lower intensity) in the flare gradual phase. Particularly in the gradual phase of some long-duration events there is evidence for long-lasting coronal heating, and energy transport to the chromosphere to generate gradual-phase flare ribbons may be by thermal conduction from a strongly heated corona. In this scenario the main question is the origin of the high-temperature coronal plasma in the late phase of a flare.

The long-standing electron beam model is currently facing some observational challenges, in particular high resolution imaging observations force the required beam flux of electrons to ever higher number densities, with attendant uncertainties about the physics of the coronal beam propagation. Additionally, limb flares show that the HXR sources are much lower in the atmosphere than can comfortably be explained in the beam model, given what else is known about the characteristics of the atmosphere and the emitting electrons. Crucial therefore is to directly detect signatures of the electrons in flight through the corona: at present only (occasional) coronal and chromospheric sources are seen, with the link between the two still speculative.

<u>Tasks</u>

- II-6-1: Observe, at high cadence, the evolution of electron and ion distributions from thermal to non-thermal, with high dynamic range and spatial resolution in the corona and chromosphere.
- II-6-2: Detect signatures of electrons in flight through solar atmosphere.
- II-6-3: Observe the dynamic response of the lower atmosphere to identify the energy transport mechanism.
- II-6-4: Identify the evidence of Alfven waves that carry the energy from the reconnection site to the chromosphere.

<u>Key observations</u>

- High dynamic range (>100) HXR imaging spectroscopy capable of detecting and mapping spatially the bremsstrahlung emission from electrons in transit through the corona simultaneously with footpoint emission and looptop emission if present;
- high temporal resolution (<0.1s) direct imaging observations of the chromospheric emission free of atmospheric seeing effects, to allow a detailed timing analysis of footpoint emission, including conjugate footpoints;
- UV or EUV imaging spectroscopy of the corona and chromosphere, with excellent spatial and spectral resolution, and very well-characterised line shapes, to study the development of plasma heating, turbulence, and ion and electron distributions (inc. non-Maxwellian) in the flare atmosphere;
- High spectral resolution Ly-a imaging spectroscopy/spectropolarimetry to look for the spectral signature of charge-exchange interactions between a proton beam and ambient hydrogen, and the polarization signatures of beam excitation.
- Gamma-ray imaging / imaging spectroscopy with very large area detectors to properly located and characterise locations and temporal evolution of accelerated ions, of which we have only had glimpses so far.

III: Mechanisms driving the solar cycle and irradiance variation

III-1: Measure flow structures in the solar convection zone that drive the regeneration of solar magnetic fields

Background

Flows in the solar convection zone play essential roles in driving the regeneration of solar magnetic fields. The essential ingredients are the differential rotation, meridional circulation, and turbulent convection. The differential rotation acts as the so-called omega effect in solar dynamo models. The meridional flow may play a role transporting the magnetic flux in the latitudinal direction. The convection plays an important role in dispersing the magnetic flux on the surface.

The solar differential rotation on the surface has directly been measured by the Doppler velocity or by tracking some features, and the internal rotation over the solar convection zone has been estimated from helioseismic approaches by measuring the modes of 5 min oscillation. The surface meridional flow has been measured by the photospheric feature tracking and local helioseismology. The meridional flow in deeper layers is not known (various researchers reach different conclusions). The global dynamics of the solar convection zone is expected to be controlled by anisotropic stresses due to rotating turbulent convection (Hanasoge et al. 2016). A better understanding of the large-scale flows could therefore emerge from measurements of subsurface convection. Puzzling helioseismic results by Hanasoge et al. (2012) indicate that convective velocity amplitudes are much lower than expected from numerical simulations. In this respect it is essential to better understand the influence of rotation on the large scales of convection (Featherstone & Hindman 2016).

Missing observations at present include the characterization of differential rotation, the meridional flow, and convection features at high latitudes and/or in the deep convection zone. The flow structures at high latitudes will partially be characterized by Solar Orbiter. For measurement of flows in the deep convection zone, long-term continuous observations from an out-of-the-ecliptic viewing angle may be required: this is an opportunity for a future mission.

Tasks

The following tasks are defined for understanding the flow structures in the solar convection zone:

- III-1-1: Measure meridional flows, differential rotation, and convective flows at high latitudes.
- III-1-2: Measure meridional flows in the deep convection zone.
- III-1-3: Characterize large-scale convective flows in the solar interior.

Key Observations

- Measure full-disk photospheric intensity and Doppler velocity for helioseismology from out-of-ecliptic vantage point to assess the flows at high latitudes. [III-1-1, III-1-2]
- Measure full-disk photospheric magnetic fields [III-1-1, III-1-3]
- Instrument requirements: Δt (temporal cadence) < 1min, t > 3 years, Δx (spatial sampling) ~ 1 arcsec, field of view = whole sun [III-1-1, III-1-2, III-1-3]

III-2: Locate and trace signatures of the global magnetic flux in the Sun

Background

For understanding the origin of the solar magnetic fields, it is essentially important to identify the formation depth of the magnetic flux that is responsible for the global solar magnetic fields or to detect the deepest locations of the rising flux tubes. The formation of the polar fields or the mechanism of the polar field reversal also needs to be understood for the strength of the solar activity of the next cycle.

It is widely believed from theoretical considerations that the global solar magnetic fields are formed near the base of the convection zone (CZ). The signature from observations on the other hand is rather limited; among the reported potential evidence for deep-seated magnetic flux near the base of CZ are the variation of the rotation speed with 1.3 yr period (Howe et al. 2000) and the variation of the sound speed (Baldner and Basu 2008) from global helioseismology, and the variation of meridional flow speed (Liang and Chou 2015) from local helioseismology. The effort will continue to solidify these results. It is also desired that the theoretical suggestion (Rempel, Schüssler and Tóth 2000) that there is jet-like flows inside the toroidal flux tubes near the base of CZ be also tested observationally.

Tasks

In the following, tasks for detection of the global magnetic flux in the deep convection zone are listed:

- III-2-1: Search for solar-cycle related acoustic anomalies in the deep convection zone.
- III-2-2: Search for flows in deep-seated flux tubes near the tachocline.
- III-2-3: Determine how the polar-field patchy structures are formed by horizontal flux transport for understanding the origin of polar magnetic fields.

Key Observations

- Measure full-disk intensity and Doppler velocity for helioseismology by two spacecraft with a large-angle viewing angles (e.g. one from the Earth and the other from L5) [III-2-1, III-2-2]
- Measure full-disk photospheric magnetic fields for monitoring the convection zone before the rise of active regions [III-2-1]
- Measure high-resolution polar magnetic fields [III-2-3]
- Instrument requirements: Δt (temporal cadence) < 1min, t > 3 years, Δx (spatial sampling)~ 1 arcsec for full disk [III-2-1, III-2-2], but Δx 0.1 arcsec for polar fields [III-2-3]

III-3: Quantify the role of turbulence in the solar dynamo

Background

All solar dynamo models share a common premise, i.e., that differential rotation creates toroidal fields from poloidal fields. Models differ, however, in the mechanism proposed to close the loop by generating poloidal fields from toroidal fields. The two dominant dynamo paradigms are 1) the Babcock-Leighton dynamo model, in which large-scale poloidal fields are generated by the destabilization, rise, emergence, and dispersal of magnetic flux tubes from the interior, and 2) the convective dynamo model, first proposed by Parker. The convective dynamo model basically argues that kinetic helicity generated by rotation and stratification produces magnetic helicity, which then is transferred from small to large scales resulting in magnetic self-organization. In particular, the turbulent alpha effect allows small-scale eddies to ultimately generate large-scale poloidal fields.

The convective dynamo relies on the Coriolis force (solar rotation) playing a significant role in generating kinetic helicity. At the solar photosphere, however, convective time scales are much shorter than the solar rotation period, at least on solar granulation spatial scales (supergranules exhibit sensitivity to the Coriolis force, e.g., Langfellner et al., 2015). Thus, the convective dynamo paradigm is likely to depend upon kinetic helicity being generated below the solar surface. Closer to the surface, chaotic turbulent flows may still lead to the generation of magnetic fields in a local dynamo process, but this takes the form of a small-scale magnetic carpet, and cannot explain a cyclical solar cycle. It may be, however, that that the local dynamo is somehow coupled to the global dynamo, or indeed that the small-scale local dynamo can help to maintain the magnetic self-organization that is the large-scale dynamo (Hotta et al. 2016).

Tasks

- III-3-1: Observe small-scale kinetic and current helicities in the photosphere for determining potential mechanisms for an alpha effect.

  High-resolution measurements of the spectral transfer of magnetic helicity from small to large scales and its transport through the solar atmosphere would provide evidence for a turbulent alpha effect. Local helioseismic measurements and granulation- tracking measurements probe kinetic helicity, at least on supergranule scales which are sufficiently large and slow to be sensitive to the Coriolis force (Duvall & Gizon 2000, Hathaway 2013, Langfellner et al. 2014, 2015)

- III-3-2: Measure kinetic and magnetic energy spectrum in small-scale turbulent convection for understanding local dynamo near the surface and its impact on the global dynamo.

  High temporal/spatial resolution measurements of solar magnetic fields and flows can shed light on turbulent processes associated with a local dynamo. Since the local dynamo does not generate helicity, any evidence of magnetic helicity in the quiet sun photosphere indicates a coupling of the global and local dynamo consistent with a turbulent alpha effect. In general, comparing active and quiet solar regions will provide information about local-global dynamo coupling.

Key observations

- Ultra-high resolution and sensitivity vector magnetic fields and flows at the photosphere (III-3-1; III-3-2)
  Note: DKIST will do this; space-based would allow uniform-quality data over time without atmospheric effects.
- Helioseismology to probe subsurface kinetic helicity. (III-3-1)
- UV observations could help quantify magnetic helicity transfer through the solar atmosphere. (III-3-2)

III-4: Understand the mechanism of solar irradiance variations

Background

The comparison of solar and climate data sets over long time scales displays correlations that point to a solar influence on climate variability, at least in the pre-industrial age. Although the detailed mechanism by which solar activity affects the climate is still a topic of intense study, the variation in the Sun's radiative output, quantified in terms of spectral solar irradiance (SSI) and total solar irradiance (TSI), are thought to play a key role (Gray et al. 2010).

The brightness of the Sun changes as a function of the level of activity on the solar disc. On timescales from hours to months the evolution of active regions and their rotation onto and off the visible disc cause variations in TSI as well as in radiation from X-rays to IR wavelengths. Over the 11-year solar cycle, the rise and fall of solar magnetic flux and activity leads to significant variation of the SSI at short wavelengths. Whereas in the visible most of the radiation reaches the Earth's surface and heats it directly, the shorter wavelength radiation controls the chemistry, dynamics, and ionization state of the terrestrial upper and middle atmosphere, which are coupled to the troposphere and hence to the Earth's climate (Haigh 2007; Domingo et al. 2009; Solanki et al. 2013).

There is a qualitative disagreement between measurements and models of SSI, in particular in the near- and middle-UV and the visible spectral ranges. It is not clear if the problem lies in the models, due to missing knowledge of the brightness of small-scale magnetic features in the UV, or if it lies in the instruments, due to degradation of the sensitivity of SSI measurements. The discrepancy is most severe in the range from 250 nm to 400 nm. Recent measurements suggest a factor of three to six stronger variability than previous observations and models. This is only possible if compensated by anti-phase changes in the visible (400 nm to 700 nm), for which no physical mechanism has been identified, however (Ermolli et al. 2013).

The modelled and measured UV irradiance records introduce highly contrasting variability in the stratosphere with rather different impacts on climate. Most critical are the relative amplitudes of the irradiance changes below and above 242 nm, responsible for ozone production and destruction, respectively. High resolution imaging of magnetic elements in the UV below and above 242 nm and in the visible are needed to provide key observations to determine the cause of the discrepancy between various irradiance data sets and unravel the role of solar UV irradiance changes in the ozone balance in the Earth's atmosphere. Only a space mission with high resolution UV imaging capabilities can obtain statistically significant amounts of the necessary data. No mission has so far had these capabilities.

By entering these brightness values into state-of-the-art models, the SSI at the sampled wavelengths can be computed. It is equally important to measure the total irradiance as well as spectral irradiance in multiple wavelength bands in parallel. The combination of high-resolution and irradiance measurements along with appropriate modelling will resolve this important controversy and finally provide the climate community with the correct variation of SSI at different time-scales. The two parallel approaches of together using, on the one hand, high-resolution data and modelling and, on the other hand, direct TSI and SSI measurements, will also provide irradiance data of unprecedented stability, as the measured and modelled TSI and SSI can be used to calibrate and correct each other for jumps and degradations.

The photometric variability of the Sun over its activity cycle is noticeably lower than that of other Sun-like stars with a similar level of chromospheric activity (Lockwood et al. 2007). Although a number of possible reasons for this have been proposed, no clear answer has emerged so far. Is the Sun unusual? By determining the brightness of magnetic features in exactly the same wavelength bands as used to observe other stars, it will be possible to make reliable models of solar/stellar irradiance variations at these wavelengths. SSI measurements at the same wavelengths, when taken together with the models, can be used to compare with stellar measurements far more consistently than done so far.

<u>Tasks</u>

- III-4-1: Measure brightness of elemental structures in multiple UV (200–400 nm) and visual wavelengths in magnetized and non-magnetized regions with the aim of understanding the mechanism of UV irradiance.
- III-4-2: Construct solar irradiance model based on full disk magnetic fields for understanding of the mechanism of UV irradiance obtained in III-4-1.
- III-4-3: Understand low photometric variability of the Sun relative to other Sun-like stars.

<u>Key observations</u>

- High-resolution ($\Delta x \le 0.1$") UV images at a range of wavelengths including Lyα, 170 nm, 200-242 nm, 242-300 nm, 320-360 nm, CN bandhead, G-band, the Strömgren b and y bands and the Kepler and PLATO wavelength ranges (~420-900 nm, 500-1000 nm) [III-4-1 and III-4-3]
- Photospheric vector magnetic fields at high resolution ($\Delta x \le 0.1$") [III-4-1 and III-4-3]
- High resolution imaging and magnetic field measurements to be repeated regularly in regions with different magnetic flux (quiet Sun and active regions) and at different parts of disk (μ=0.1…1) [III-4-1]
- Photospheric vector magnetic fields over the full solar disk ($\Delta x \le 1$") [III-4-2 and III-4-3]
- Chromospheric image: Lyα, Mg II h & k, Ca II H & K (III-4-1)
- Observations of TSI with a stability of 0.001% per year, corresponding to a stability of better than 0.01 W/m^2 per decade, and an absolute accuracy of 0.01% [III-4-1 and III-4-2]
- Observations of SSI at a range of wavelengths starting at 115 nm, including the ozone and oxygen absorption bands in the UV, the Strömgren b and y bands and the Kepler/PLATO bands in the visible [III-4-1 and III-4-2 and III-4-3]
- Long-term photometry (t > 5 year, half solar cycle) in photometric bands used in stellar surveys, e.g. Strömgren b and y bands over full solar disk [III-4-3]

III-5: Explore the deep internal structure of the Sun

Background

While the acoustic p-mode oscillations have been used for understanding inside the Sun through estimating the flow speed in the convection zone, the g-mode oscillations, which are believed to be trapped in the radiative interior, have not been detected despite extensive efforts including the space observations. The g-modes are more suited for investigating the core and radiative region of the Sun than the p-modes. Due to the evanescent nature of the g-modes in the solar convection zone, the expected velocity amplitudes on the solar photosphere from theoretical estimates (Gough 1985; Kumar 1996; Belkacem et al. 2009) is 10^{-4}–10^{-1} cm/s in the frequency range of 10–200 μHz are much smaller than the observed p-mode amplitudes of ~10 cm/s over a few mmHz range. The 10-year long-term observations by SOHO have given the upper limits of 0.1–1 cm/s in the g-mode amplitudes over the frequency of 30–300 μHz. A further high-precision measurement is required for the detection.

Tasks

- III-5-1: Detection of g-mode for understanding its excitation and travel of waves in the Sun (and for investigating the solar core)

Key observations

- A high-precision Doppler measurement for detecting the velocity amplitude of 0.01 cm/s

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Appendix C

Existing facilities

Facility	Description
CURRENT (not exhaustive, ground-based high resolution facilities restricted to ≥ 1m)	
Hinode	Optical spectropolarimetry, EUV spectroscopy, SXR imaging
IRIS	UV spectroscopy and imaging
NuSTAR	Astronomical X-ray satellite with solar capability
Proba-2	EUV imager, radiometers
RHESSI	Hard X-ray spectroscopy and imaging
SDO	UV/EUV imaging, EUV irradiance, helioseismic & magnetic imager
SOHO	Coronagraphs, radiometer, heliospheric imager and *in situ* instruments remain
STEREO	Two-spacecraft mission, EUV imagers, coronagraphs, heliospheric imagers, particles
GOES	X-ray spectral irradiance, particle data, full-disk EUV imaging
NST	1.6m ground-based optical/NIR, imaging and spectropolarimetry
SST	1m ground-based optical telescope, imaging and spectropolarimetry
NVST	1m ground-based solar optical telescope, imaging and spectroscopy
GREGOR	1.5 m ground-based solar optical telescope, imaging and spectropolarimetry
BiSON	Network of optical telescopes for low-degree helioseismology
MLSO	Ground-based coronagraphs and polarimeter, full-disk imaging
NSO-Synoptic	Chromospheric and photospheric magnetograms, helioseismic measurements
ALMA	mm-wave array with solar capabilities
LOFAR	Low-frequency radio astronomy array with solar capabilities
Nobeyama	Radio interferometer, 17 GHz and 34 GHz
IN CONSTRUCTION	
Solar Orbiter	Out of the ecliptic, solar encounter mission. EUV imaging & spectroscopy, visible spectropolarimetry, coronagraphs and in-situ instruments. Launch February 2019
Parker Solar Probe	Solar encounter mission, *in-situ* instruments, heliospheric imager. Launch August 2018
Proba-3	Formation flying coronagraph, launch late 2018
DKIST	4m ground-based optical/NIR. First light 2020
EOVSA	Frequency-agile 15-element radio interferometer, 1-18 GHz
CHSR	Frequency-agile 100-element radio interferometer, 0.4-15 GHz
FUTURE POSSIBILITIES	
EST	4m ground-based optical/NIR
FASR	Frequency-agile ~200-element radio interferometer, 0.5 MHz - 21 GHz

COSMO LC	1.5m ground-based visible/NIR coronagraph/polarimeter

Appendix D

SOT members and their areas of expertise (as a table)

Luis Bellot Rubio	Instituto de Astrofísica de Andalucía, CSIC, Spain	Solar magnetic fields
Mats Carlsson	University of Oslo, Norway	Chromospheric physics
Lyndsay Fletcher	University of Glasgow, UK	Solar flares
Sarah Gibson	National Center for Atmospheric Research, High Altitude Observatory, USA	Solar corona and sun-earth connections
Laurent Gizon	MPS, Germany	Helioseismology
Hirohisa Hara	NAOJ, Japan	Solar activity
Kiyoshi Ichimoto	Kyoto University, Japan	Solar observation and instrumentation
Kanya Kusano	Nagoya University, Japan	Solar flares and coronal mass ejections
David McKenzie	NASA-MSFC, USA	Solar flares and magnetic reconnection
John Raymond	Harvard Smithsonian CFA, USA	Solar wind
Takashi Sekii	NAOJ, Japan	Helioseismology
Toshifumi Shimizu	ISAS/JAXA, Japan	Magnetic activities and heating in photosphere-chromosphere-corona
Sami Solanki	MPS, Germany	Solar magnetism and space climate
Ted Tarbell	LMSAL, USA	Magnetic fields, space instrument development & operation

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Appendix E

Town Hall Meetings and Community Q&A Discussions

E.1 Q&A at Hinode-10

The first "Town Hall"-type meeting was conducted during the Solar-C session at the Hinode-10 meeting in Nagoya, Japan, primarily for the purpose of introducing the SOT to the community and starting a dialogue. After presentations of the SOT charter and some preliminary studies of instrument concepts in Japan, an extensive Q&A with the full audience was conducted, addressing the goals and objectives of the SOT and the NGSPM. Discussion during this Q&A touched upon the scope of science disciplines to be considered for NGSPM (solar physics, as distinct from heliospheric physics and space weather operational missions). We introduced the concept of a Town Hall at the American Geophysical Union meeting in San Francisco for further dialogue with the community, and began tentative plans for such a Town Hall.

E.2 Town Hall at AGU

The second major Q&A session was a Town Hall meeting at the AGU in San Francisco. Being in December, this occurred approximately half-way through the SOT's deliberations. The SOT members were joined by agency representatives from NASA and JAXA, who presented the rationale for chartering the SOT. As the purpose of this Town Hall was to report on our progress, and take additional input from the community, we described the two phases of our work plan (define objectives, and then recommend mission concepts), and described our progress during the first phase. We then summarized for the attendees the white paper exercise (see Section 2.2 below) and how that input was enhancing the SOT's discussions. These reports were followed by an extensive Q&A, including discussion about the agencies' expected budget, timeframe, and mission scope (small/medium/large).

E.3 UK Community Meeting

During the UK Solar Physics Community's annual missions forum, attended by around 50 community members, the purpose, membership and progress of the SOT was described, based on the presentations given at the AGU Town Hall. The outcome of the call for white papers was also summarised. Each UK author or co-author of a white paper was invited to make a 1-slide presentation and poster of his or her concept or idea. This was then followed by a discussion about the alignment of the NGSPM-SOT, objectives, process and possible outcomes with the UK's own priorities in solar physics.

E.4 Japanese Community Meetings

Community meetings were organized multiple times by JSPC (Japan Solar Physics Community) to discuss science objectives and future directions of solar physics in Japan. The first symposium (3-4 October 2016, ISAS/JAXA) was an opportunity to discuss key science objectives based on the NGSPM-SOT study at the early phase with the community. Four sub-groups formed in the JAXA Solar-C WG presented science objectives and mission concepts based on Epsilon opportunity and identified scientific issues to be addressed in the next meeting, which was the JSPC annual meeting on 20-22 February 2017 at ISAS/JAXA. In the meeting, the Japanese NGSPM-SOT members gave a series of reports on science objectives of solar physics based on the NGSPM-SOT studies, followed by updates of Solar-C mission as well as Epsilon-class mission concepts for primarily addressing scientific issues. At the same time, the future plan for ground-based facilities was also discussed associated with the future direction of space observations. Then, some schedule updates on the announcement of opportunity in JAXA were reported to the community during the ASJ (Astronomical Society of Japan) meeting (Fukuoka) on 17 March 2017. The JSPC also held a one-day meeting on 13 July 2017 at NAOJ for having community consensus toward the coming Epsilon AO, with inputs from NGSPM-SOT report as well as study updates from the JAXA Solar-C WG.

E.5 Q&A at Hinode-11

At the conclusion of the Hinode/IRIS joint science meeting in May-June 2017, in Seattle, Washington, a 75-minute session was allocated for a presentation and Q&A regarding the Draft Report of the NGSPM-SOT. Following a PowerPoint presentation of the main points of the Draft Report, a Q&A with the audience discussed initial reactions of the community to the findings and preliminary recommendations.

Appendix F

Epsilon mission system configuration

Epsilon rockets are the JAXA’s solid-fuel 3-stages vehicle and have successfully launched Hisaki in 2013 and Arase (ERG) in 2016. The epsilon rocket is used for competitively chosen medium-sized focused missions (<150M dollars class), which one launch is expected every 2 years in the 2020’s. The Epsilon can install a 500 kg satellite into a sun-synchronous polar orbit at an altitude of 570 km. If the weight of the satellite can be reduced to 450 kg, the altitude can be increased to 600 km. In the case of a launch at the solar maximum (2024), a thruster system is needed onboard to keep the orbit if the sun-synchronous condition is required for a period longer than one year. The payload volume available in the rocket fairing has a height of about 5.4 m with a diameter of 1.9 m, which tapers toward the top edge (0.236 m in diameter at the top edge) above 2.8 m height level.

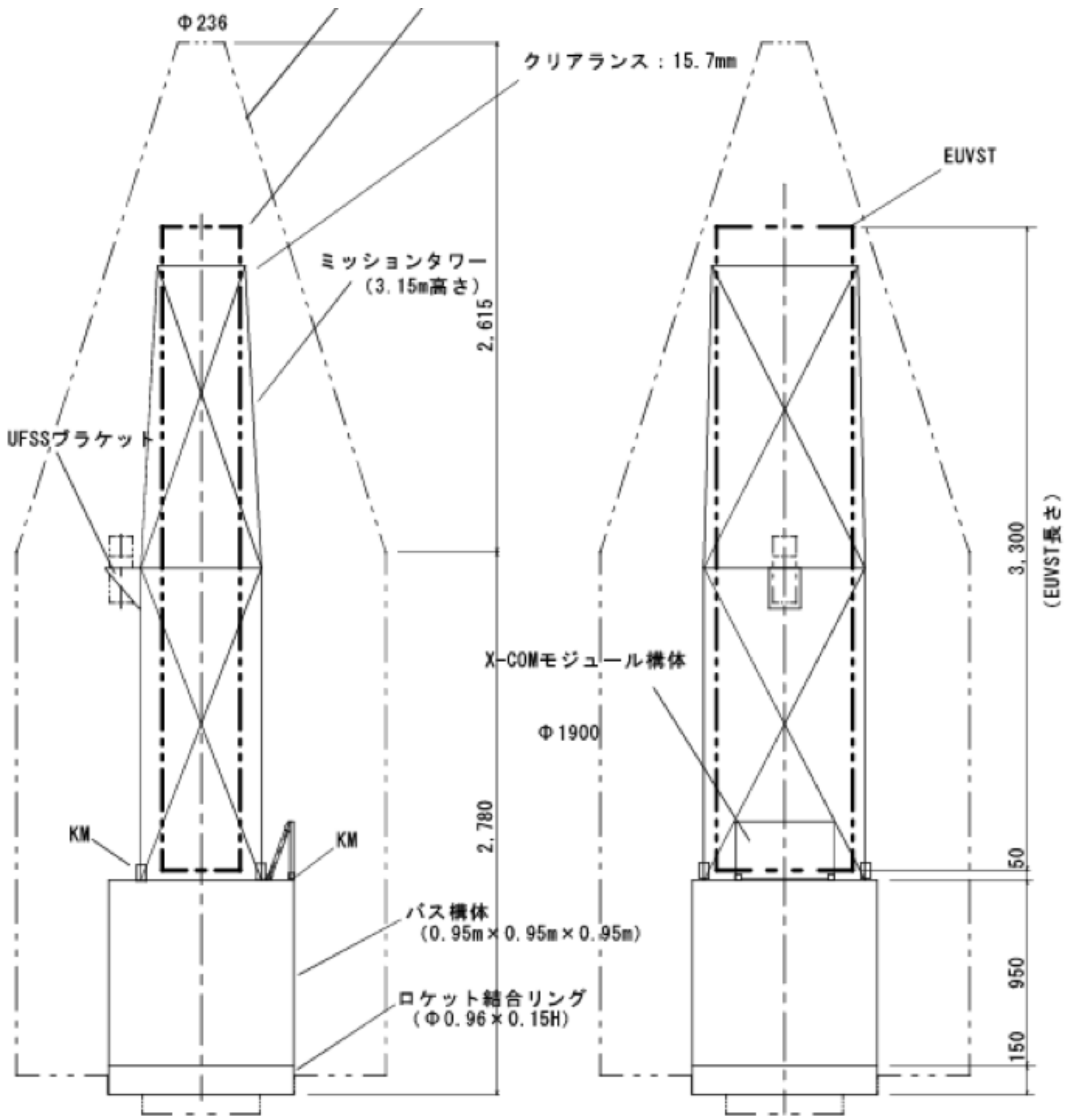

Figure F-1: Spacecraft structural baseline configuration

A spacecraft bus, jointly developed by ISAS/JAXA and an industrial contractor, has been used in previous Epsilon rocket launches (Hisaki, Arase), which has about 1.1 m height. The following descriptions are based on this spacecraft bus, although a different spacecraft bus can be applicable. When the instrument is equipped in vertical configuration on the spacecraft bus, the maximum length of the instrument on the bus is 4.3 m, so that it requires a tapered structure at the top edge (0.236 m in diameter). If the instrument dimension is a rectangular shape with the size of 0.4 x 0.7 m at the top edge, the maximum length of the instrument is reduced to about 3.3 m (Figure F-1). The mission truss structure is used to mount the instrument. Table F-1 summarizes a design of the spacecraft based on this spacecraft bus with this dimension. By adapting the Ultra Fine Sun Sensor (UFSS) and high resolution gyroscope (IRU) to the attitude control system, the short-term (10 s) pointing stability may be on the order of 0.2 arcsec at 3 sigma. For the mission concept for high spatial resolution instruments, it is important to consider an image stabilization system inside the instrument for guaranteeing the performance at intermediate frequencies and the micro-vibration control for the high frequency range. A high-speed telemetry channel (X-band 8 Mbps available in Japan, a higher telemetry system to be developed in Japan, or a higher telemetry system to be provided by international collaboration) shall be added to the system in addition to the standard S-band 2Mbps telemetry channel.

Table F-1: Epsilon spacecraft design example with baseline configuration

Items	Specification
External dimensions	Bus: 1.0 m x 1.0 m x 1.1 m (excluding the solar array paddles) The instrument: 0.4 x 0.7 x 3.3 m (See Figure X)
Mass	451 kg (dry weight), 481kg (at liftoff), if the instrument is assumed 155 kg
Orbit	Sun synchronous polar orbit Altitude 570 km (for 500 kg), 600 km (for 450 kg) A thruster system to maintain the orbit
Power	Maximum total power allowed: 1,000 W
Communications	Commands: S-band House-keeping telemetry: S-band 2Mbps Mission telemetry: X-band (QPSK) 8Mbps or a higher telemetry system
Mission Data handling	Standard Bus recorder: 2 Gbytes, write/read speed 15 Mbps Mission data recorder: TBD Gbytes in the instrument
Attitude control	3-axis body control, Pointing accuracy much improved with Ultra Fine Sun Sensor (UFSS) and high resolution Gyroscope (IRU), Tracking the solar rotation
Lifetime	Longer than 3 years (desired)