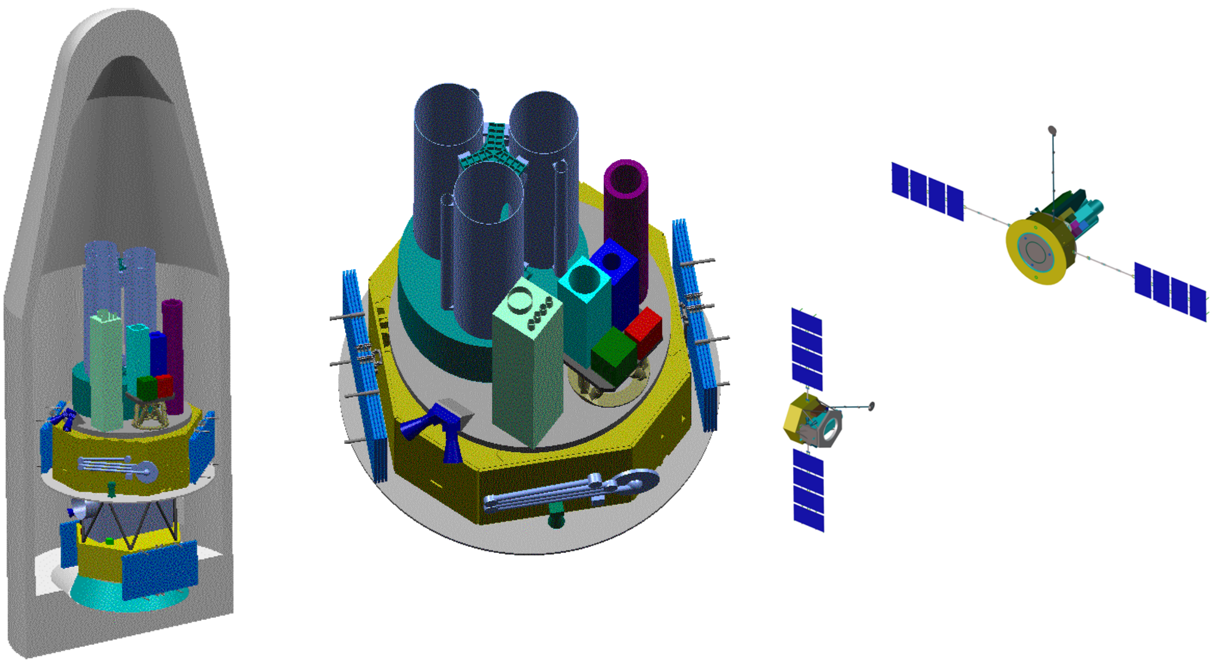
HiRISE

High Resolution Imaging and Spectroscopy Explorer

Ultrahigh resolution, interferometric and external occulting coronagraphic science: Great leap in solar physics



Proposal in response to the ESA science programme call for White Papers in the Voyage 2050 long-term plan

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1. Executive summary

1.1 Science Objectives

Recent developments in solar physics have shown the definitive role of magnetic field and waves at the chromosphere-corona interface and deep in the inner corona, where dramatic and physically dominant changes occur. Advances in new-generation ultra-high resolution, interferometry and coronagraphy now provide the opportunity to make transformational progress in addressing the finest details of these processes through observations of the solar atmosphere from the photosphere to the corona, leading to new insights of the solar interior from the core to the photosphere.

Despite excellent progress in recent years in understanding the link of the solar atmosphere to coronal dynamics and coronal heating there remain major crucial questions that are still unanswered. Limitations in the observations are one important reason. Both theoretical and observational considerations point to the importance of small spatial scales of impulsive energy release, dominant dynamics and extreme plasma non-uniformity. Consequently, high spatial resolution, broad temperature coverage with high temperature fidelity and sensitivity to velocities and densities, are all critical observational parameters. Current instruments lack one or more of these much-needed properties for major leaps. Recent novel developments in coronal heating and diagnostics emphasize that high spatial resolution observations, especially combining spectroscopic and imaging observations, are absolutely necessary to make major progress on this fundamental problem of modern astrophysics. In particular, the critical region between the chromosphere and corona, the transition zone (or, in a broader context: the Interface Region), may need to be addressed as well as measuring the nature and connectivity of magnetic fields from the photosphere to the corona, directly.

There are at the centre four major thematic issues that address the global understanding of the solar environment through the magnetic field emergence and dissipation, and its influence on Earth. They are interlinked and also complementary: the internal structure of the Sun determines the surface activity and dynamics that trigger magnetic field structuring, of which evolution, variation and dissipation will, in turn, explain the coronal heating onset and the major energy releases that feed the influence of the Sun on Earth.

There are four major thematic issues:

1. to reveal and understand the detailed structure and evolution of the solar atmosphere. Ultrahigh resolution imaging and spectroscopy is needed to trace the Sun's magnetic field structure and evolution from the deep photosphere into the corona. To make a leap one needs to reveal the links between the building layers of the Sun's atmosphere. One will have to track the complete evolution of magnetically-driven processes from the smallest scales to the largest; address magnetic emergence, evolution and reconnection; the development and regression of active regions; the development and nature of transient events in the magnetised atmosphere; the onset and fine-structure of flares from the smallest (e.g. nanoflare scales) to the largest (sometimes even white light flares), and the propagation of magnetic activity through the different regimes of the solar atmosphere.
2. to answer longstanding and fundamental solar physics questions: how are the chromosphere, transition region and corona heated? How does magnetic energy build in the Interface Region? What is the role of fine structure (strands)? Of convective motions? Waves, wave and/or ion-cyclotron, shock acceleration, dissipation and energisation? How and where are the different components of the solar wind, slow and fast, accelerated? How are Coronal Mass Ejections accelerated? What is the strength of the coronal magnetic field? What are the magnetic building blocks of the corona? Its topology, connectivity and coupling role? A unique set of coronagraphs, externally occulted for inner corona access, and ultraviolet for direct magnetic field measurement in the corona, has the privilege to directly address these major questions.
3. to probe the internal, sub-photospheric structure of the Sun, the transfer from the radiative to the convection zone, the role of the tachocline, the links between internal flows and the magnetic cycle. Magnetic activity and its variations are the consequences of the internal regimes of convection. *g*-modes and long-period *p*-modes are the only known modes capable to penetrate deeply enough to constrain the solar dynamics of the core. These modes need to be looked for at the limb and in the UV, where their amplitude is expected to be 4-5 times greater than with full-disc measurements, and, with multi-points velocity measurements of increased sensitivity. In addition, second-generation observations of local magnetically influenced oscillations guarantee the correct understanding of the transition from inside to outside the Sun, from sub-surface to surface flows and manifestations.
4. to measure and understand the profound influence of the Sun on Earth and the consequences for human life through the predictions of long-term climatic changes. A new-generation of instruments needs to

measure solar shape, solar constant, stratospheric UV and IR flux, Lyman-alpha imaging and *in-situ* measurements of the solar wind at L1. They are necessary to measure and follow in great details the solar inputs received on Earth and their local and global variations with high precision.

To make the above scientific leaps, instrumentation at the L1 Lagrangian point, would provide metre class FUV imaging and spectro-imaging, EUV and XUV imaging and spectroscopy, magnetic fields measurements, and ultimate coronagraphy by a remote external occulter (2 satellites in formation flying 375 m apart: coronagraph on chaser satellite). This major and state-of-the-art payload will allow characterization of temperature, densities and velocities in the solar upper chromosphere, transition zone and inner corona with, in particular, 2D very high resolution multi-spectral imaging-spectroscopy, *direct* coronal magnetic field measurement: a unique set of tools to understand the structure and onset of coronal heating. The scientific objectives are natural complements to the Solar Orbiter and Parker Solar Probe-type missions that lack duty cycle, high resolution, spatial, spectral and temporal multi-temperature diagnostics and full coronal magnetometry. For major progress one needs to address:

- fine structure of the chromosphere-corona interface by 2D spectroscopy in FUV at very high resolution;
- coronal heating roots in inner corona by ultimate externally-occulted coronagraphy;
- resolved and global helioseismology thanks to continuity and stability of observing at L1 Lagrange point;
- solar variability and space climate with a global comprehensive view of UV variability as well.

<u>Fine structure of the chromosphere-corona interface</u>. The most interesting and novel observations can be made by a co-phased interferometer of 1.4 meter baseline coupled to a UV double monochromator and Imaging Fourier Transform Interferometer to join high spatial, temporal and spectral resolutions, and to a visible 8 channels Vector Magnetograph. By using interferometry in the UV with a spectral-imaging mode, HiRISE will allow remote sensing discoveries of the solar surface and atmosphere with an unprecedented spatial resolution of 20 km on the Sun that current missions, some even planned to have closer distance to the Sun, will never be able to achieve! High-resolution EUV and X-ray imagers and spectrometer complete the view with both high-resolution context views and detailed (to the tenth of an arcsec) in depth imaging.

<u>Coronal Heating</u>. This problem has been around for many decades and initial progress has been made. It is now known that the origin of this once mysterious heating is most probably magnetic in nature. However, one still needs to probe the magnetic field further with high spatial, spectral, temporal and velocity resolution in order to distinguish between, for example, magnetic wave heating, small scale reconnection events or convective leakage. Further, the nature of the magnetic field needs to be accurately understood in order to construct a clear scenario of the magnetic building blocks of the solar atmosphere. Connectivity is a key ingredient that is poorly understood at present. Different phenomena such as active regions, "quiet Sun" and coronal holes are all likely to have different heating mechanism(s). HiRISE will provide us with the revolutionary opportunity to determine this with very high resolution in the transition zone and with its giant externally occulted coronagraph (formation flying) in the visible, IR and UV, with direct measurement of the coronal magnetic field very near the limb (1.01 solar radii).

<u>Ultimate Magneto-Helioseismology</u>. HiRISE's advantage is also its permanent Sun viewing orbit which, alike SOHO or SDO, allows resolved and global magneto-helioseismology. This is the third breakthrough of HiRISE, with its unique package of instruments for limb oscillations in the UV (predicted highest *g*-modes sensitivity), intensity, global and resolved observations, and high-resolution full and resolved Sun velocity oscillations (with the Magneto Optical Filter, MOF, in particular).

<u>Solar Variability and Space Climate</u>. The fourth breakthrough is the thorough set of diagnostics to study solar variability. A complete new set of solar constant, global and spectrally resolved irradiance monitors, will be implemented and coupled to enhanced Lyman α imaging and a unique solar limb shape (and solar differential rotation) monitor. To this third set, the magnetograph and MOF bring the magnetic field information, and the coronagraphs, the coronal extension of the field. This will directly address the nature of UV variability and its climate consequences. EUV, X-ray imagers and X-rays and gamma-rays spectrometers complete the variability survey together with i*n-situ* measurements of the solar wind at L1 (particles and magnetic field) that allow monitoring the development of interplanetary perturbations and study the geoeffectiveness.

1.2 Feasible Technical and Programmatic Aspects (Potential Mission Profile, Model Payload)

<u>Potential Mission Profile Summary.</u> HiRISE will achieve its impressive aims with a major mission scenario involving two satellites in formation flying 375 m apart at the L1 Lagrangian point. The main spacecraft uses a modified Herschel platform and the chaser spacecraft, forming a giant externally occulted coronagraph, a

Herschel-like platform. Novelty is also in state-of-the-art, new instruments, allowing kilometric resolution and reasonable mass and volume, like the SOLARNET interferometer. The numerous high technologies and new features of HiRISE will lead to novel insights into how the Sun works from the interior to the outer corona and to the Earth. With orders of magnitude improvement in spatial resolution but also in sensitivity (UV spectro-imaging, diameter oscillations, and more), HiRISE has the potential to resolve major open questions in modern solar physics and to bring in important discoveries. For the first time a mission will address directly the key component in understanding the Sun: the magnetic field structuring. We will resolve it in much smaller features to analyze thoroughly the Sun's magnetic activity on multiple scale: time variability, evolution and fine-scale structure of the dynamic chromosphere, transition region and corona, origin, confinement, acceleration and release of energy, heating of the chromosphere and corona. HiRISE will complement the *in situ* observations of the Parker Solar Probe (PSP) and fly-by of Solar Orbiter and build upon HINODE, SDO and PROBA-3 moderate spatial resolution observations.

Payload, platforms and mission scenario were studied with Thalès Alenia Space in 2007, 2010 and 2015 (ESA M3 & M4). This is an international concept with participation e.g. from Russia, China or US. The cost conscious approach of re-using Herschel and Heschel-like platforms allows a mission at the Lagrange point L1 with extreme coronagraphy thanks to formation flying. Telemetry in Ka band with the Cebreros antenna allows an impressive average downlink superior to 13.6 Mbits/s (41 Mbits/s 8h/day) while HiRISE requires about 12 Mbits/s. The expected volume and format of the data coming from the various instruments will be larger than any previous solar physics spacecraft but small compared to current Earth observation missions. No particular difficulties are foreseen to handle, process and archive data in an operation facility.

POTENTIAL MISSION SUMMARY TABLE	
Launch vehicle	Soyuz-Fregat with 2 satellites in "stacked composite" configuration (< 1700 kg)
Orbit	Halo orbit around the Lagrange L1 point
Formation Flying	2 satellites 375 m apart controlled to 4-6 arcsec alignment
Spacecrafts	main satellite: Herschel platform re-use chaser satellite: Herschel-like platform (smaller: functional chains)
Mission duration	3 years nominal (extended: 6 to 12 years) – launch possible in 2029 (solar cycle 25)
Data handling	~ 12 Mb/s downlink using Ka-band high rate modulation, a 40 cm antenna and the 35 m Cebreros antenna – or New Norcia if upgraded (< 90% capacity)

<u>Potential Scientific Payload Concept</u>. The dynamics of the chromosphere and corona is controlled by the emerging ubiquitous magnetic field. The plasma dynamics in each magnetic thread is believed to be linked to the formation of filaments, each one being dynamic on its own, in a non-equilibrium state. Mechanisms sustaining these dynamics, their manifestation in oscillations or waves (Alfvén or magneto-acoustic), require both very high-cadence, multi-spectral observations, and high resolution. HiRISE is combining ultrahigh resolution and coronagraphy to achieve:

- resolution (0.02”) chromosphere-corona interface characterization with a 1.4 m UV-FUV telescope or equivalent (3 x 500 mm telescopes, independent or combined) and 3D imaging spectro-polarimetry;
- eclipse-like extreme coronagraphy of inner corona (up to 1.01 R_S) in vis., UV, NIR by Formation Flying between 2 satellites 375 m apart: Fe XIV, He I D3 & 1083, Fe XIII 1075 & 79, Lyman series & O VI;
- continuity, waves and oscillations, global and local magnetoseismology, EUV & XUV complementary imagers and spectrometers, TSI and photometers, and particles and magnetic fields experiments.

The HIRISE payload may be distributed on two satellites 375 m apart with respective payloads (instruments) of 500 and 150 kg. The major payload includes the 3 telescopes of SOLARNET and 10 instruments (3 in the I2P, the Interferometer Instrument Package), in a volume of Ø2.8 m by 3 meters high:

- SOLARNET Interferometer (3 x 50 cm telescopes, 1.4 m baseline, actively cophased and pointed) 100 kg
- I2P: UV Imaging Spectrometer (UVIS) — subtractive double monochromator and IFTS 60 kg
- I2P: high resolution Vector Magnetograph (VM) 60 kg
- I2P: Chromospheric Imaging Camera (CIC) 40 kg
- EUV Diagnostic Spectrometer (EUDS) 55 kg
- EUV and X-rays Imagers (EUXI) 63 kg
- High Energy Burst Spectrometers (HEBS) hard X-rays and gamma-rays, 10 keV to 600 MeV 20 kg
- Dual Magneto Optical Filter (DMOF) for full Sun magnetograph and oscillations 60 kg
- SUAVE, solar activity, limb oscillations, and shape changes (full Sun Lyα, 160 & 220 nm imaging) 25 kg
- SOLSIM, solar ultraviolet spectral irradiance monitor 9 kg
- PREMOS II (TSI and Photometers with fast sampling rates and redundancy) 8 kg

On the Chaser satellite, in formation flying at 375 m (on a Herschel-like platform), we have:

- SuperASPIICS Green, IR (1074.7 nm) and UV giant externally occulted coronagraph 120 kg
- HLI, Heliospheric Large FOV (20°) Imager 20 kg
- SWIP *in-situ* Solar Wind Instrument Package (magnetic field, shocks, thermal plasma) 10 kg

The payload is a unique set of instruments to truly follow the magnetic field from its generation in the convective zone by local helioseismology, to its development and structuring in the chromosphere and transition zone, and energy release through waves, flux tubes motions, tangled magnetic field strands or the combination of these processes in the corona. The very complete UV to Near-IR externally occulted coronagraph allows imaging and spectroscopy (polarization) very near the limb in the inner corona. Direct magnetic field measurements are carried from the photosphere to the corona (Hanlé effect polarization of Lyman series).

HiRISE would serve a large community of more than 70 Co-Is in 15 countries around the world. In addition, we expect very significant participations, in this new proposal, of our Chinese (or US) colleagues In this context, the payload can be ambitious gaining orders of magnitude on previous recent missions (HINODE, STEREO, SDO, PSP) or on the ones to come (PROBA-3 and Solar Orbiter). Colleagues from the Lebedev Institute (Moscow) also contribute to an instrument. In the present scheme, the 1.4 m telescope (monolithic like SOLAR-C or interferometer, the two options being open at this point), is envisaged as an ESA realisation (with or without JAXA involvement) since not in the realisation possibilities of any single country, national agency or laboratory in Europe.

HiRISE proposal at L1 Lagrange point is complementary to Solar Orbiter (and NASA PSP) to which it will bring coronagraphy, coronal magnetometry and very high resolution in the upper-chromosphere, transition zone and inner corona where most of the coronal heating physics is thought to happen through flux tubes convective motions, waves or magnetic reconnection of tangled magnetic field strands. Stereo possibilities between missions could also been envisaged. HIRISE builds upon our European competencies in EUV/XUV imaging and spectroscopy, enhances global and local helioseismology measurements, uses the revolution in high resolution made possible by interferometry, and adds the breakthrough of formation flying to achieve close limb coronagraphic observations. Furthermore, continuity of observation at the L1 Lagrangian point allows unprecedented new limb and velocity oscillations search for g-modes, to understand the magnetic origin of the solar activity leading, hopefully, to predictions for coming decades.

1.3 Risk Issues

The "Stacked Composite" approach, proposed and studied by Thalès Alenia Space, for a launch by Soyuz to L1 of the two HiRISE satellites, is well dimensioned and providing a comfortable margin (> 20 %). Telemetry is evaluated to 12 Mbits/s, what is indeed high but in the cope, for instance, of the Cebreros antenna Ka-band high rate modulator 41 Mbits/s (i.e. 13.6 on 8h/day). Costs have been thoroughly evaluated by Thalès Alenia Space in 2007 (HiRISE Cosmic Vision proposal: €340M) and revised since to €500M taking into account M3 and M4 missions' evaluation by ESA in 2010 and 2015. This results is the consequent heritage of the mission (Herschel platform in particular).

There is no scientific revolution without a technological one. Both formation flying – allowing ultimate coronagraphy near the limb – and interferometry on extended objects in the Far UV – allowing the energy release at the chromosphere-corona interface to be probed, are building on this. The risk taken, reasonable in respect of the precursors and technological developments, is worth the unique results anticipated, that none of the current or planned missions will bring. Though, we are conscious that the gain in high-resolution comes in part from the FUV access of our spectro-imaging approach and from the interferometer that makes the last factor 3, from 60 to 20 km: a major step to disentangle coronal heating theories but, also, a major cost and risk issue. Accordingly, and to minimize risk, the payload is using interferometry ultrahigh resolution as an extra. The 3 x 50 cm telescopes can, indeed, be combined together towards the 2D UVIS spectrograph but they can also be used *independently* and *simultaneously* for multi-spectral multi-temperature sensing by the 3 instruments in the I2P since to each telescope is directly linked one major instrument: the FUV 2D spectrograph (UVIS), the Vector Magnetic Field Instrument (VM) and the Chromospheric Imaging Camera (CIC). This way, risk is minimized and innovation preserved with access to interferometry, a major key to discoveries. Nevertheless, a monolithic telescope option will also be considered as a trade-off even if heat evacuation is even more critical for larger telescopes.

2. Detailed Science Objectives

2.1 Context

SOHO, HINODE, STEREO, RHESSI, SDO and IRIS have been very successful missions addressing many aspects of solar and heliospheric physics and, consequently, pointing out the areas in need for a better and deeper understanding of the Sun and heliosphere. They were truly worthy missions but progresses can now be achieved in areas where SOHO and other missions stopped: high resolution of the surface and atmosphere, coronagraphy of the inner corona with a direct measurement of the magnetic field, and global and local optimized magneto-helioseismology. The series of recent Japanese and US missions, simply do not have the resolution (in particular at the crucial interface between the chromosphere and corona) nor the coronagraphs to access one of the most enduring enigma in astrophysics: the existence of a million degree solar corona.

Ultra-high resolution (Damé *et al*., 1998a; Damé and Derrien, 2002; Damé, 2003, 2006) is a further development of the SIMURIS, SPI, SOLARNET concepts. It is a significant step further than any other proposed mission by implementing a global concept that delivers not only extreme solar coronagraphy (direct coronal magnetic field measurement), but also the very high spatial and spectral resolutions in the thin UV, FUV and EUV lines required to understand the confinement in the transition zone, the interface between the chromosphere and corona. It includes high resolution and performing EUV/XUV imaging and spectroscopy, very novel revolution in high resolution made possible by interferometry, and adds a helioseismology package with an enhanced resolved velocity experiment (the DMOF, Dual Magneto Optical Filter) and a multi-points global velocity measure (GOLF-NG), that could potentially address the so-much sought-after *g*-modes detection.

Altogether, our science and the associated enabling mission is now proposing further improved and innovative, European and international (China or US and Russia) instruments, building upon our previous responses to ESA for M2 (2007) and M3 (2010) with the HiRISE Mission, noticeably with considerable overlaps in 2010 by the follow-up SolMex proposal (Hardi et al., 2012), "la rançon du succès". HiRISE's extensive instrumentation covers all the required scientific objectives for an in-depth solar physics understanding.

2.2 Major Scientific Themes

The global understanding of the solar environment through the magnetic field emergence and dissipation, and its influence on Earth, is at the centre of the four major themes addressed by HiRISE. They are interlinked and also complementary: the internal structure of the Sun determines the surface activity and dynamics that trigger magnetic field structuring which evolution, variation and dissipation will, in turn, explain the coronal heating onset and the major energy releases that feed the influence of the Sun on Earth. The major themes of HiRISE are:

1. to reveal and understand the detailed structure and evolution of the solar atmosphere. Ultra-high resolution imaging and spectroscopy will trace the Sun's magnetic field structure and evolution from the deep photosphere to the corona. It will reveal the links between the building layers of the Sun's atmosphere. We need to track the complete evolution of magnetically driven processes from the smallest scales to the largest, address magnetic emergence, evolution and reconnection, the development and regression of active regions, the development and nature of transient events in the magnetised atmosphere, the onset and fine structure of flares from the smallest (e.g. nanoflare scales) to the largest (white light flares), and the propagation of magnetic activity through the different regimes of the solar atmosphere.

2. to answer longstanding and fundamental solar physics questions: how is the solar atmosphere heated? How does magnetic energy build upon the corona? What is the role of fine structure (strands)? Of convective motions? Waves, wave and/or ion-cyclotron, shock acceleration, dissipation and energisation? How and where are the different components of the solar wind, slow and fast, accelerated? How are Coronal Mass Ejections accelerated? What is the strength of the coronal magnetic field? What is the magnetic building block of the corona? Its topology, connectivity and coupling role? With a unique set of coronagraphs, externally occulted for inner corona access, and ultraviolet for direct magnetic field measurement in the corona, has the privilege to directly address these questions.

3. to evidence the internal, sub-photospheric structure of the Sun, the transfer from the radiative to the convection zone, the role of the tachocline, the links between internal flows and the magnetic cycle.

Magnetic activity and its variations are the consequences of the internal regimes of convection. g modes and long-period p modes are the only known modes capable to penetrate deeply enough to constrain the solar dynamics of the core. These modes will be searched at the limb and in the UV where their amplitude is expected to be 4 to 5 times greater than with full-disc measurements, and with multi-points velocity influenced oscillations guarantee the correct understanding of the transition from inside to outside the Sun, from sub to surface flows and manifestations.

4. to measure and understand the profound influence of the Sun on Earth and the consequences for human life through the predictions of long-term climatic changes. For this, stratospheric UV and IR flux inputs, Lyman alpha imaging and *in-situ* measurements of the solar wind at L1 are needed to measure the solar shape and solar constant. They are necessary to measure and follow in great details the solar inputs received on Earth and their local and global variations with high precision.

We can reformulate these 4 themes of as:
• fine structure of the chromosphere-corona interface by 2D spectroscopy in FUV at very high resolution;
• plasma heating roots in inner corona by ultimate externally-occulted coronagraphy;
• resolved and global helioseismology thanks to continuity and stability of observing at L1 Lagrange point;
• solar variability and space climate with a global comprehensive view of UV variability as well.

Fine structure of the chromosphere-corona interface. The most interesting and novel observations will be made by a cophased interferometer of 1.4 meter baseline coupled to a UV double monochromator and Imaging Fourier Transform Interferometer to join high spatial, temporal and spectral resolutions, to a visible 8 channels Vector Magnetograph (VM), and to a chromospheric imager. By using interferometry in the UV with a spectro-imaging mode, will allow remote sensing of the solar surface and atmosphere with an unprecedented spatial resolution of 20 km on the Sun that Solar Probes or Orbiters, despite their closer distance to the Sun, will never be able to achieve! High resolution EUV and X-ray imagers and spectrometers complete the view with both high resolution context views and detailed (to the tenth of an arcsec) in depth imaging.

Atmospheric Heating. This problem has been around for many decades and initial progresses have been made. It is now known that the origin of this once mysterious heating is most probably magnetic in nature However one still needs to probe the magnetic field further with high spatial, spectral, temporal and velocity resolution in order to distinguish between, for example, magnetic wave heating, small scale reconnection events or convective leakage. Further, the nature of the magnetic field needs to be accurately understood in order to construct a clear scenario of the magnetic building blocks of the solar atmosphere. Connectivity is a key ingredient that is poorly understood at present. Different phenomena such as active regions, "Quiet Sun" and coronal holes are all likely to have different heating mechanisms. One needs now to determine the magnetic field with very high resolution in the transition zone and with e.g. a giant externally occulted coronagraph (formation flying) in the visible, IR and UV, with direct measurement of the coronal magnetic field very near the limb (1.01 solar radii).

Ultimate Magneto-Helioseismology. A permanent Sun viewing orbit which, alike SOHO or SDO, allows resolved and global helioseismology, magneto-seismology. This is the third breakthrough much needed for science progress, measuring limb oscillations in the UV (predicted highest g modes sensitivity), intensity, global and resolved observations, and high-resolution full and resolved Sun velocity oscillations (with e.g. the Dual Magneto Optical Filter, DMOF, and GOLF-NG multi-points velocity measurements).

Solar Variability and Space Climate. The fourth breakthrough is the thorough set of diagnostics to study solar variability. A complete new set of solar constant, global and spectrally resolved irradiance monitors, are implemented and coupled to enhanced Lyman α imaging and a unique solar limb shape (and solar differential rotation) monitor. To this third set, potential instruments like the VM and DMOF would bring the magnetic field information, and the coronagraphs, the coronal extension of the field. This will directly address the nature of UV variability and its climate consequences. EUV, X-ray imagers and X-rays and gamma-rays spectrometers complete the variability survey as well as i*n-situ* measurements of the solar wind at L1 (particles and magnetic field) that mallow to monitor the development of interplanetary perturbations and study their geoeffectiveness.

The high-resolution imaging of the solar atmosphere will be better than in past missions by more than an order of magnitude. These capabilities in concert will enable us to analyze thoroughly the time-variability, evolution and fine-scale structure of the dynamic chromosphere-corona interface, to study fully the Sun's magnetic activity on multiple scales, to investigate energetic particle acceleration, confinement and release, and to reveal plasma and radiation processes underlying the heating of the chromosphere and corona.

The relevant minimum observable scale in the solar atmosphere may be of the order of 10–30 km since smaller scales will probably be smeared out by plasma micro-instabilities (such as drift waves). This scale range is comparable to the photon mean free path in the chromosphere. Slightly larger scales can be expected in the corona (though gradient across coronal loops may also be a few km). Altogether this situation is rather fortunate because we have access to higher resolutions in the far UV and EUV than in the visible. In the EUV and UV, the emission lines are generally thin, i.e. not affected by the optically thick transfer conditions (which prevail in the visible and near UV lines accessible from ground or used on Hinode) and we can expect to see structures with scales 10 to 30 km. In the visible, thick transfer in the atmosphere blurs the signature of structures and nothing smaller than 70–100 km should be observed. This means that with a single instrument of meter class diameter we have the appropriate, scientifically justified, spatial resolution for both the far UV (20 km in the C III line 117.5 nm) and the near UV (60 km in the Ca II K line λ396.3 nm).

Furthermore, observations of the EUV spectral range provide detailed plasma diagnostics in the solar atmosphere across the broad temperature range from tens of thousands to several million K, covering the chromosphere, transition region and active corona. Analysis of the emission lines from trace elements in the Sun's atmosphere provides information on plasma density, temperature, flow speeds and the structure and evolution of atmospheric phenomena. A range of lines from different elements provides a detailed element abundance diagnostic capability. In this respect, HiRISE ideally complements the *in situ* plasma studies that are carried by a solar probe.

A breakthrough in high spatial resolution observations in the UV (*20 km is 20 times more spatial resolution than any previous solar instrument in space*) should allow to understand in finer physical details processes like magnetic heating in coronal loops (temperature profiles, time dependence, spatial local ionization of heating processes) but, also, by access to visible wavelengths, the coupling between turbulent convective eddies and magnetic fields in the photosphere. Another scientific objective is the plasma heating and acceleration processes and thermal inputs of flares and microflares and their fine magnetic field structures. Heating, acceleration, flares and microflares but also internal structure (*g*-modes) are "big" questions that indeed, after years of limited observations, now deserve a dedicated and efficient program: *ultra-high resolution imaging and spectro-polarimetry*.

2.3 The Big Science Questions

"Big" science questions in Solar Physics are:

- the interface heating process; discriminate between theories of wave/impulsive plasma heating
- how and where the solar wind is accelerated
- the nature of solar flares and CME's
- the origin of the sunspot cycle (the variability)
- the solar interior

These questions have to be directly addressed in the near future, since both the atmospheric heating and acceleration process (or processes) and the nature of solar flares are linked with the magnetic field which is the key in understanding these dissipation mechanisms SINCE THEY NECESSARILY INVOLVE SMALL SCALES. Helioseismology of the deep solar interior is a problem that requires the detection of long-period modes and, if accessible, *g*-modes, the internal gravity modes. Since *g*-modes are probably best observed at the limb, as indicated by MDI (Kuhn *et al*., 1997), and in the UV (2 orders of magnitude better sensitivity with the diameter than with intensity or velocity), a dedicated instrument is devoted to that measure (SUAVE). The origin of the solar cycle is a variability problem and an important issue for life on Earth. We need to investigate the consequences of solar variations (constant, UV, diameter) on the Earth climate or, on shorter time scales, for Space Weather issues.

The Sun is a fantastic physical laboratory, orders of magnitude from the plasma, temperature and magnetic concentration available on Earth, and is the Rosetta stone of Stellar Physics since for a long while a single star will not be observable in so much details (imagine stellar limb oscillations?).

All these questions must be addressed by HiRISE that will provide new views, diagnostics and give answers to those not addressed by the *in situ* plasma missions such as: Parker Solar Probe, Solar Orbiter and/or InterHelioProbe). For the rest, we still have to do extremely well with high-resolution of the magnetic structuring, coronal diagnostics, magneto-helioseismology for solar interior (dynamo, *g*-modes), coronal magnetic field, Lyman Alpha, solar shape and solar variability for Space Weather and Space Climate.

2.4 High-resolution Paradigms

The supergranulation network, which dominates the chromospheric plasma dynamics, is apparent in the EUV emission pattern as seen by the SUMER instrument on-board SOHO shown in Fig. 2.1. Magnetograms

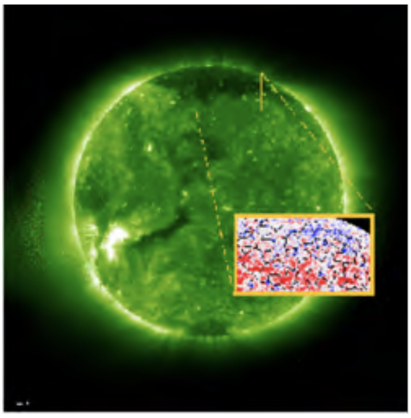

Figure 2.1 – SUMER observations of the solar-wind source regions and magnetic structure of the chromospheric network. The insert shows the measured Doppler-shifts of Neon ions, indicating blue shifts, i.e. outflow, at the network cell boundaries and lane junctions below the polar coronal hole, and red-shifts (down-flow) in the network regions underlying the globally closed corona (adapted from Hassler et al., 1999).

from SOHO have revealed the ubiquitous appearance of small magnetic bipoles at the solar surface. After emergence, the polarities separate and are carried to the network boundaries by the supergranular flow, where they merge with the pre-existing network flux. This leads to flux cancellation, sub-mergence and reconnection events. The magnetograms also show that the magnetic field exists in the network in two components side-by-side, i.e. in un-cancelled unipolar fields or in a carpet of closed loops and flux tubes. The small loops will of course emerge or contract downwards and collide, and thus constitute a permanent source of energy, which can be tapped by the particles through magnetic field dissipation. Recent numerical simulations suggest that many of the bipolar structures can only be resolved at a resolution of 20 km or less.

As a consequence of these observations, theoretical ideas about the origin of the solar wind have been put forward (see review of Axford and McKenzie, 1997; Cranmer, 2010; Ofman, 2010) according to which the wind originates in the chromospheric network, and draws its energy from high-frequency waves generated by magnetic reconnections of the dynamic and complex fields prevailing there. Above mid-chromospheric altitudes the field expands rapidly, fills the overlying corona and guides the solar wind mass flux, emanating from the open chromosphere, where the plasma is created by photo ionization. Plasma outflow has indeed been detected by SUMER on-board SOHO and is illustrated in Fig. 2.1. The mechanisms responsible for the origin of the slow solar wind remains unidentified. Small scale reconnection, high altitude reconnection in streamers, spicule-induced shocks and MHD wave dissipation have been proposed. Different signatures are expected from each mechanism: small-scale jets, strong downflows in streamer legs, formation of shocks, or propagating waves, respectively. HiRISE with its proposed unprecedented spatial resolution will for the first time: a) reveal the fine structure of the network and provide definitive answers to the question of where and how the solar wind originates; b) allow images and 2D spectro-imaging to reliably disentangle spatial and temporal structures; c) observe the source signatures of the plasma (reconnection, dissipation). EUV spectral lines will play a key role with temperature and velocities diagnostics.

For example, small-scale magnetic activity is expected to continually produce waves, energetic particles, and rapidly-moving plasma. The dissipation of the waves could involve cyclotron damping. This process is observed to operate in the distant solar wind (Marsch, 1991) and known to heat the plasma. Detailed observations of such key plasma processes originating in the transition region and heating the extended outer corona afterwards are now needed.

The magnetohydrodynamic waves generated in the photosphere by convective motions of the granules and supergranules are primarily of low frequency. In the small-scale magnetic structures of the strongly inhomogeneous network fields higher-frequency waves could be excited up to the kHz range. Such waves would certainly transfer very effectively wave energy, e.g. into the transverse kinetic degrees of freedom of the protons, and particularly the heavy ions, thereby heating them to very high coronal temperatures, a process for which the UVCS instrument and the SUMER experiment on SOHO, or lately by Hinode, have found evidence in the strong Doppler-broadenings of emission lines (Kohl et al., 1997; Antonucci et al., 1997; Wilhelm et al., 1998; Tu et al., 1998; Banerjee et al., 2007). Due to its investigation potential in the UV, transition zone heating sites of the corona, and the high sensitivity and spatial resolution of its instrumentation, HiRISE will for the first time be able to see very dim emissions, concentrated for high contrast in emissivity, for instance in plasma confined in small loops (threads of 10-20 km?), or loop profiles (Priest, 1999a).

The major part of the magnetic flux permeating the solar photosphere outside sunspots is concentrated in small (scales of 20 km or so) flux tubes of kilo-gauss field strength. The structure and dynamics of these fundamental elements of the near-surface magnetic field has profound implications for a number of basic questions, e.g.:

– how do magnetic foot-point motion, wave excitation, flux cancellation and reconnection contribute to the flux of mechanical energy into the corona?
– in which way do the emergence, evolution and removal of magnetic flux elements determine the magnetic flux budget of the Sun? Is there a local dynamo operating on the scale of granulation?
– what is the origin of the facular contribution to the variability of the Solar constant?
– what is the physics of the interaction between convection and magnetism?

Answers to the questions require the study of magnetic flux elements on their intrinsic spatial scale. The high-resolution of the imagers, spectro-imagers and magnetograph is intended to monitor the emergence, dynamics, twist, shearing, mutual interactions and possible coalescence and subduction below the surface in order to follow the evolution and scrutinize the life cycles of magnetic flux elements. Coupled with the resolved oscillations of instruments like DMOF (a Dual Magneto Optical Filter), the rotation below the surface can be addressed and, accordingly, the relation between convection and magnetism.

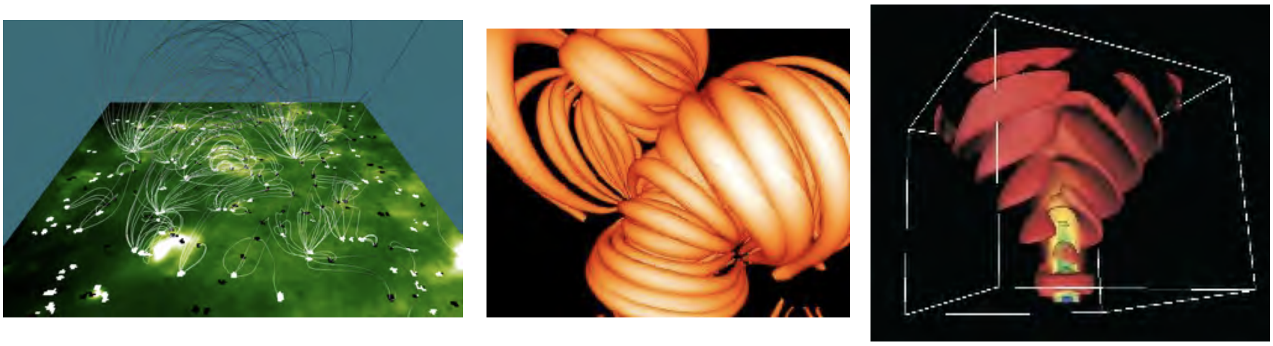

Figure 2.2 – Modelling magnetic fields extension in the chromosphere and corona is now possible and will gain from higher resolution and atmospheric height sampling. In order to extrapolate with confidence to the corona, Vector Magnetic Fields are required in the photosphere; direct magnetic field measurement in the corona would help to validate the extrapolations.

Tangled magnetic fields associated with MHD waves and electric currents are believed to play a dominant role in the magnetic field restructuring, leading to energy dissipation. Modelling has significantly progressed over the last years and delivered promising "paradigms" for this dissipation, either from tangled fields, as suggested and studied by Klimchuk and co-workers (Klimchuk, 2006; Klimchuk and Lopez Fuentes, 2006), by leakage of oscillations (waves) at the level of the upper chromospere and transition zone (and in spicules) as studied by e.g. De Pontieu, Erdélyi and co-workers, and Jefferies noticeably (see De Pontieu *et al*., 2003, 2004, 2007, 2014; Erdélyi, 2006; Erdélyi *et al*., 2007; Jefferies *et al*., 2006), or even by direct convection simulations like in the work of Peter *et al*. (2005a,b, 2006). These three approaches to dissipate energy and create fine structures (observed in the transition zone by, e.g., De Pontieu *et al*., 2007, 2012, 2013, 2014), have all three their success evidences but desperately need to be disentangled by direct observations with higher spectral and spatial resolutions and direct magnetic field.

A key scientific objective of HiRISE is to study the new emergence and the cancellation of photospheric magnetic flux (the latter is the disappearance of opposite polarity regions in close contact), and to investigate the consequences of such processes for the overlying global coronal magnetic loops and for the chromospheric and transition region magnetic network above. Flux cancellations are known to be associated with or at the origin of various active phenomena, such as filament formation and eruption, evolution of small points of emission bright in radio or X-rays, or the occurrence of flares. Magnetograms combined with UV, FUV, EUV and soft X-ray images as well as FUV and EUV spectra, and the direct magnetic field measurements in the inner corona by e.g. a Lyman coronagraph channel, are the key data necessary to understand the bearing that small scale magnetic activity has on the transition zone and inner corona.

The Yohkoh, SOHO, TRACE, Hinode and now SDO extreme ultraviolet and soft X-ray telescopes have provided and yet provide a rich harvest of coronal images, though only at a spatial resolution not much better than 1 arcsec. These images (see, for example, Strong *et al*., 1994; Schrijver *et al*., 1997) illustrate the existence of fine-scale structures in the corona, such as polar plumes and thin post-flare loops, and reveal continuous dynamics occurring on all resolved scales in particular the finest. There is also strong evidence that the actual brightness structures lie well below the best current spatial resolution. This points to the need for still higher spatial resolution. The active Sun has still not been imaged with sufficient resolution! The early triggering phase of solar flares and small activity regions and the evolution of point-like events or bright X-ray spots will be monitored, with simultaneous observations in relevant wavelengths and foot-point (photospheric and chromospheric) magnetic field measurements being carried out (see also Amari et al., 2014). The wide coverage of coronal temperatures by the visible-light, UV, FUV, EUV, and X-ray telescopes would enable complete images to be obtained in fast cadence. From these, the density and temperature distributions can reliably be derived, such that the traits of coronal heating processes in current sheets, shock fronts, or acceleration in small explosive events and rapid plasma jets might become clearly visible and be resolved in time and space.

2.5 Coronal Dynamics, Heating and Magnetic field

The energy that heats the corona and accelerates the solar wind and coronal mass ejections (CMEs) originates in sub-photospheric convective motions. The physical processes that transport this energy to the corona and convert it into thermal, kinetic, and magnetic energy are not fully understood. Space missions, and in particular SOHO and Hinode, have greatly advanced our knowledge about coronal heating, solar wind acceleration, and CMEs, but many key questions remain unanswered. A detailed understanding of physical processes in the corona is important not only for explaining the origins of space weather, but also for establishing a baseline of knowledge in plasma physics that is directly relevant to the Sun, other stars, and astrophysical systems ranging from the interstellar medium to black hole accretion disks.

Different physical mechanisms for heating the corona probably govern closed magnetic loops, active regions, and the open field lines that give rise to the solar wind (Priest, 1999b; Taroyan and Erdélyi, 2009). Both densities and volumetric heating rates decrease rapidly with distance from the photosphere, but the coronal heating rates *per particle* remain large in the extended corona (Withbroe, 1988; Cranmer *et al*., 1999). This, combined with remote and *in situ* evidence that heating continues in interplanetary space (Marsch, 1999), implies that processes responsible for heating, wind acceleration, and CME ejection are dynamically important below and above the coronal base. An empirical description of the primary acceleration region (in the transition region and inner corona) of the wind and CMEs is especially crucial to determining how plasma properties at 1 AU are established.

We now need to test ion-cyclotron heating in coronal holes: the width of the O VI line in SOHO/UVCS observations increased dramatically in the range 1.5–2 solar radii above the polar coronal holes. This line width has been interpreted as the signature of the dissipation of high-frequency collisionless ion-cyclotron waves. In particular, the EUDS spectrometer will characterise the line width of O VI, Mg X and other emission lines (e.g. S VI, Fe XII, O V, He II, S X, Ne VIII, Si XII – listed in increasing Zion/Aion value) in polar coronal holes in the range 1.5–2 solar radii. Each of these ions is resonant with a different portion of the ion-cyclotron wave spectrum. Measurements of their line widths therefore provide a test of the ion-cyclotron wave theory. They will also test alternative interpretations that suggest the line width dependence on the adopted coronal electron density profiles (Raouafi and Solanki, 2006).

There is a growing realization that the innermost 0.5 solar radii (R_{Sun}) of the solar atmosphere is dominated by different physics than the extended corona at larger heliocentric distances. The chromosphere, transition region, and coronal base are strongly collisional and exhibit a complex magnetic topology, whereas the extended corona is relatively collisionless and uniform, with expansion of field lines into interplanetary space. Despite these local differences, the extended corona must be driven by energy that has made its way out through the lower layers. The lower solar atmosphere and corona are indeed efficiently coupled by the transport of non-thermal energy from the convection zone and by downward thermal conduction of heat from the corona. The nature of the outward energy flux is not known, but tangled magnetic fields associated with MHD waves and electric currents are believed to play a dominant role, as we saw previously (Klimchuk, 2006; Klimchuk and Lopez Fuentes, 2006; Erdélyi, 2006; Erdélyi *et al*., 2007; Peter *et al*., 2006, Tomczyk *et al*., 2007). Dissipation of this energy, from tangled fields, foot-point convective motions or waves — the 3 "theoretical paradigms" of heating to disentangle by direct observations — heats the coronal plasma along single or multi-threads (Schmelz *et al.,* 2010), drives the solar wind and propels CMEs. Understanding the physics of the characteristically different regions of the atmosphere necessitates studying these regions on structurally important scales, matching the 10 – 20 km spatial scale of magnetic elements in the solar photosphere. Studies of the temperature distribution of the corona indicate that the filling factor of emissive structures is ~8% of the area resolved by EIS (Winebarger *et al*., 2008). Resolving structures on a scale of 0.1" to 0.7" in the transition region and corona would allow us to probe these fundamental elements of the atmosphere's structure. Additionally, recent studies of flows in active regions (Bryans *et al.*, 2010; Peter, 2010) indicate that there may be spatially unresolved flows near key magnetic domain interfaces (Baker *et al.*, 2009) at which there are changes in the characteristic properties of the atmosphere such as temperature and density. Measuring these properties along with bulk velocity, through the transition region, where changes of regime are significant, is key to building working pictures of this interface, and thus to connect the high-beta and low-beta parts of the solar atmosphere.

The question of impulsive heating versus wave heating can also be approached with much more confidence at sub-arcsecond scales. In the lower chromosphere, the ability to spatially resolve coherent wave motions at sub-arcsecond scales has already been shown to be of great use in estimating energy flux in these relatively small-scale magnetic concentrations (Jess *et al.*, 2009). However, stable observing conditions and visibility across a greater height (and thus temperature) range in the solar atmosphere are required if we are to understand the characteristic energy flux in more than a handful of such elements. This requires moving to the FUV and EUV ranges. Spatial resolution and ability to measure dynamics and diagnostics in lines formed from the lower transition region (C III, H I) to the lower corona (Mg X) will allow us to measure the propagation of energy in waves through these regimes and measure the resulting energy absorbed by the local plasma. In this way, we can understand the contribution of these and other fine scale structures, such as those seen in active regions, to the energy flux that passes into the corona and solar wind.

Plasma flows are key signatures of non-thermal energy transport by wave propagation and of energy dissipation by magnetic reconnection. Observation of these flows in the transition region and corona is essential to address sources of coronal activity – heating, transient events, particle acceleration, solar wind, and irradiance variations. Through measuring line profiles and line intensities of several tens of EUV lines,
These would provide answers to many long-standing and challenging questions:

While magnetic fields emerging in the solar atmosphere control the structure, dynamics and heating of the solar corona, these fields remain essentially unattainable with the present low corona instrumentation. Indeed, after 40 years of space coronagraphy, the lower corona (<2.5 R_{Sun}) remains practically unobserved since LASCO-C1 on SOHO, aimed at observing the inner corona (with a Fabry-Perot setup), had a fairly large level of instrumental straylight, and since its Fabry-Perot does not survive the SOHO hibernation. The COR1 coronagraphs on Secchi/STEREO are simple imaging systems with no diagnostic capability, and also suffer from large instrumental straylight. Ground-based coronagraphs are affected by seeing and atmospheric conditions, and are practically limited to a FOV < 1.5 R_{Sun}. These observations are further background limited as Rayleigh scattering of the Earth atmosphere always dominates the flux received by the instrument. Full Stokes polarimetry of the Fe XIII 1074.7 nm line, giving information on the line of sight magnetic field magnitude, were obtained only recently (Lin *et al.*, 2000; Lin *et al.*, 2004, Tomczyk *et al.*, 2007) but are limited to bright, low altitude regions of the corona.

Performing high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several emission lines from the transition region and corona base out to 2.5 R_{Sun} is necessary to address the following questions:

- *How is the corona heated? What is the role of convective motions? Of waves?*
- *How are the different components of the solar wind, slow and fast, accelerated?*
- *How are CMEs accelerated?*
- *What is the strength and direction of the coronal magnetic field? Its topology?*

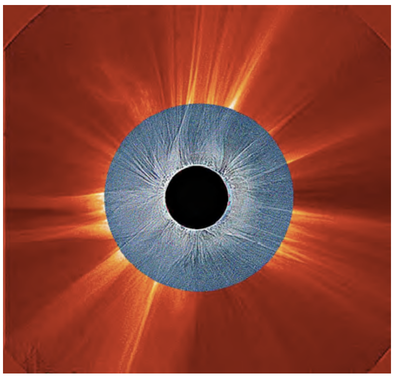

Figure 2.3 – Composite image of the corona of the August 11th, 1999 eclipse in Iran. The inner part is made of the White Light image obtained with a radial gradient neutral filter. The outer part is the Lasco-C2 (SoHO) image (from Koutchmy *et al.*, 2004). Note the perfect correspondence of the radial fine structures. The proposed "SuperASPIICS" coronagraph is intended to achieve the same quality as the eclipse observation in the inner corona with, in addition, unsurpassed diagnostic capability.

To access the inner corona (see Fig. 2.3) uninterrupted with ultra-high resolution, formation flying is an excellent solution, allowing visible spectroscopic measurements far out in the corona and near-infrared spectroscopic measurements in the low corona, and to perform magnetic field measurements. CMEs need to be observed to distinguish theories of CME initiation: the breakout model, the tether cutting model and the flux rope model. Observing evolution of the filament structure prior to eruption, recording high-speed jets that mark the reconnection site and observing the energy distribution in the post-eruptive plasma will provide discrimination between the models. We need to test theories of particle acceleration by observing pre-shock conditions and shock structure in the low corona with attempting to answer the question of how do shocks accelerate the corona. In particular, acceleration and injection mechanisms for impulsive Solar Energetic Particle (SEP) events are controversial. Wave-particle interactions or even CME-driven shocks have been proposed as the source of the enhancement. Measuring both X-rays and gamma-rays from 10 keV to an impressive 600 MeV for large flaring events will confirm theories. Acceleration in shocks at heights 1.5 – 2 Rs will be characterised by measuring temperature increase of hotter lines (Mg X, Si XII) or increase in line broadening (e.g. O VI). In the lower corona we need to remotely determining the elemental composition of plasma, in particular, of solar wind source regions to compare with *in-situ* measurements in the solar wind made by other spacecrafts (Solar Probe Plus and/or InterHelioProbe).

2.6 Solar Interior and Subsurface Characterization

The two major objectives in helioseismology are: first, to detect the gravity modes (*g* modes) of the Sun; second, to build upon MDI/SOHO and HMI/SDO with an improve resolved velocity imager at higher resolution (1 arcsec) and with improved magnetic field: this to trace the magnetic field from the convective zone to the surface (local helioseismology; flows from equator to the poles over the cycle?).

g-modes are of prime importance to understand the structure and dynamics of the solar core which cannot be studied by using solar pressure modes (p modes) alone. So far the *g* modes have not been discovered by any set of instruments on-board the SOHO spacecraft. After more than 10 years, GOLF is still only suspecting some possible signatures. The 1-σ upper limit of *g*-mode amplitude at around 200 μHz is typically 1 mm/s or 0.1 ppm (Fröhlich *et al*., 1998). Given a velocity amplitude of 1 mm/s at 200 μHz, the displacement of the solar surface would be about 1.6 m p-p which is equivalent to a variation of Solar radius of about 2 μarcsec (Kuhn *et al*., 1997).

Measuring intensity fluctuations at the solar limb that perturb the equivalent solar radius signal. Appourchaux and Toutain (1997) reported to have detected *p*-modes using the limb data of the LOI instrument. In some cases the amplification with respect to full-disk integrated data is about 4, i.e. it means that a p-mode with amplitude of 1 ppm in full disk is observed with amplitude of 4 ppm at the limb (cf. Damé *et al*., 1999). This amplification factor was roughly predicted by theory (Appourchaux and Toutain, 1997). A pessimistic derivation gave 20 years for the detection of the first few *g*-modes with SOHO (Fröhlich *et al*., 1998). We seriously envisage detecting them in 16 months with the amplification factor provided by a high-resolution instrumentation.

Fundamental aspects: it is anticipated that the solar variability is driven by the Sun's internal dynamics that generates and interacts with the magnetic field, maintained by dynamo action. However, it is not easy to simulate that dynamics due to yet fairly poor observational constraints on parameters on the solar radiative zone, although of prime importance since representing 98% of the solar mass (71% in radius)! Precise observations from space are probably our only chance to obtain direct and indirect information on the solar internal dynamics and magnetic fields down to the solar core.

The magnetic field is only directly constrained just below the photosphere. SDO improved our knowledge of the convective zone but has not addressed the radiative zone with needed accuracy in detecting the gravity modes that diagnose the radiative zone and the inner core (Mathur *et al*., 2007).

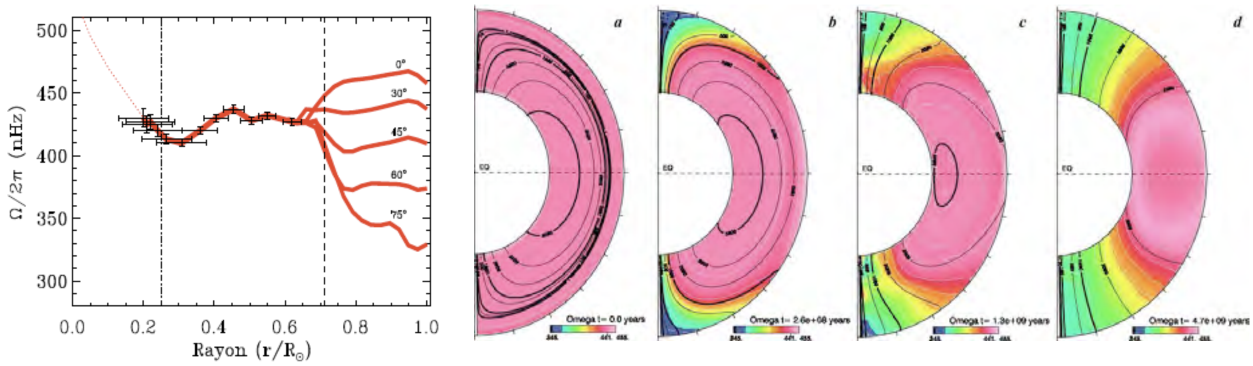

Figure 2.4 – a) Solar rotation profile deduced from acoustic mode MDI & GOLF, SOHO). Information is lacking and uncertain when reaching the core, leaving open all possible extrapolations. **b) 3D MHD simulation of the impact of a fossil field located in the radiative zone, on the internal rotation profile.** A better knowledge of the differential rotation in latitude and radius will largely constrain the 3D simulation and will help to answer the question: is there a dynamo effect in the radiative zone?

Magneto-helioseismology: the photosphere-chromosphere interface. The acoustic modes are very sensitive to the subsurface layers but global helioseismology has not extracted any information above 0.97 Rs. This region benefits from the development of local helioseismology. One needs to better describe these layers and quantify the emergent magnetic field to under-stand the evolution of the total luminosity and of the radius from one solar cycle to another one or even along one solar cycle. Recent progress came from the *f*-modes that represent the best tool to extract information from the sub-surface region. The temporal study of these modes over the solar cycle has revealed the presence of a double sheet: the region just below 0.99 Rs evolves in phase with the solar cycle, although the region above seems to be in phase opposition! A latitudinal study of these layers is extremely useful, and an independent measurement of the photospheric radius variation along the solar cycle useful to disentangle the different actors. Moreover, real constraints on the thermodynamics and magnetic properties of the region between the photosphere and the chromosphere will be possible through the analysis of several absorption lines: He, Na, K, Ca. Measure in K and Na lines would address these issues and waves propagation. One will see how the magnetic field modifies the density and pressure profile in the atmosphere, and we hope to identify and follow the chromospheric modes in this way.

2.7 Variability, Space Weather and Space Climate

The irradiance of the Sun (i.e. its brightness as measured above the Earth's atmosphere) is known to vary by 0.1% over the solar cycle. There is also some evidence for a longer term, secular variation. In spite of its small magnitude, the irradiance variation is a potential cause for climate change, probably through the variability of its UV content (10% or so). Radiometers would help to guarantee the continuity of the measurements of the solar variability. Basic questions need to be answered before we can reach an understanding of the causes of this variability:
– how does the solar luminosity (i.e. the radiation escaping in all directions) vary?
– does it change at all or is a brightening at the equator compensated by a darkening over the poles?
– why is the irradiance variability of the Sun a factor of three smaller than that of Sun-like stars?
Since the solar energy is one of the major driving inputs for terrestrial climate and since it exists some correlations between surface temperature changes and solar activity, it appears important to know on what timescales the solar irradiance and other fundamental solar parameters, like the solar shape, vary in order to better understand and assess the origin and mechanisms of the terrestrial climate changes.

The solar constant measurements performed in space by the radiometers since 1978 were modelled using the sunspots number and faculae. This allowed to reconstruct the solar constant variation till 1610 (Lean, 1997). This shows that the solar constant experienced a significant decrease during the Maunder minimum. The temperature in the northern hemisphere has also been reconstructed for the same period. The cooling of this period is known as the Little Ice Age. The similarity of the temperature and solar constant variations strongly suggests that the Maunder minimum might be the cause of the Little Ice Age. However, volcanic eruptions (major ones) also play a certain role, but their effects do not extend more than a few years.

While the diameter does not vary significantly over the solar cycle whatever the technique used (fundamental mode, Antia, 2003: < 1 mas; MDI annulus images, Kuhn *et al.*, 2004: < 7 mas; full MDI images, Damé and Cugnet, 2007: < 9 mas), neither over centuries by any significant amount (Toulmonde, 1997, who reanalysed Picard's data with the old instrument used by Picard himself: < 0.1" over 3 centuries, Wittmann, 2003 and Wittmann and Bianda, 2000, with "large" Gregory's telescopes non-affected by seeing: < 0.05" over 30 years), it could be that the oblateness changes since we know that subsurface flows are active during the cycle (MDI results). These may correlate or not with the cycle.

In order to establish without ambiguity the possible solar constant and solar shape (oblateness) relationship, a simultaneous measurement of both quantities from the same platform and in nonmagnetic lines or continua is required. The importance of the measurements for climatology is straightforward taking into account the extreme events like the Little Ice Age and the Maunder minimum.

UV and in particular Lyman Alpha irradiance has been monitored since 1977, and with EOS/SOLSTICE experiment since 2002. Since these irradiance monitoring experiments observe the Sun as a star, there is no information about the physical causes of the observed irradiance changes. To identify the causes of changes in Lyman Alpha, but also the variability in the 200-220 nm continuum (Herzberg continuum, UV-ozoneclimate interaction), one needs to compare the full disk irradiance data with images. High-resolution and continuous Lyman Alpha and Herzberg continuum images would enable progress in these sciences. Such images would make it possible to better account for the observed Lyman Alpha changes and also for a better reconstruction of a long-term Lyman Alpha data set. Since Lyman Alpha irradiance is important for the ozone changes (as well as Herzberg continuum) and the formation of the ionospheric D-region in the Earth's atmosphere, a better understanding of these variations will also be important for atmospheric science and aeronomy.

FUV/EUV observations are also likely to contribute to an important connection, namely that of the solar wind to space weather. A combination of recent results has also thrown light on the question of the behaviour of the solar wind. Studies of the magnetic topology of the periphery of solar active regions indicate that long field lines are anchored in these areas, perhaps extending to interplanetary space. Observations of hot, persistently upflowing material in these locations (Harra *et al*., 2008) suggest a source for the slow solar wind which is compounded by further remote-sensing results indicating that the composition of these upflows is consistent with that measured in situ in the slow solar wind near the Earth (Brooks & Warren, 2010). Probing these regions at transition temperatures will allow us to study in detail the locations where this material is released and to establish the veracity of such a tantalizing connection, not least its contribution to the variability of the slow solar wind and, thus, space weather in the terrestrial environment.

3. Scientific Requirements

We have, in the science part, outlined different needs and complementaries to achieve the global understanding of the Sun that we foresee, from the deep interior to the corona and heliosphere. A feasible payload to have is two satellites and 14 instruments to address these topics with the ultimate and most appropriate and performing responses.

The need for very high spatial and spectral resolution at the chromosphere-corona interface is addressed by the 1.4 m interferometer SOLARNET and its spectro-imaging instrument in the UV (UVIS). The need was outlined in the European ASTRONET exercise which recommended a "meter class" FUV telescope. This scientific need is addressed in our proposal by the UV interferometer of 1.4 meter baseline, and made of 3 "small" Ø500 mm telescopes, perfectly phased, so as to act as a single, monolithic, telescope (compact configuration). These proposed interferometer technologies have been breadboarded by LATMOS and validated through an end-to-end test from object to image reconstruction, both in laboratory, and directly on the Sun. These achievements fully secure the development of the SOLARNET interferometer as both detailed and system design issues have been addressed also. A working three telescopes imaging interferometer is currently in use and visible at LATMOS. This three-telescope interferometer, although "small" by ground standards, is large in terms of space hardware and in particular in solar physics since the largest telescope flown up to now is the 50 cm HINODE telescope. HiRISE ambitions are however "dans l'air du temps" since the SOLAR-C is also proposing a 1.5 m telescope. HiRISE has the advantage that the three telescopes can either work together or independently and simultaneously to optimize the observing capabilities. In the present proposal we suggest the 3-telescope interferometer is under ESA responsibility since too large for laboratories to realize, integrate and test. Only ESA and an industrial prime like Astrium or Thalès Alenia Space can tackle the task (and can handle the cost in view of the National Agencies present limitations).

Magnetic field direct measurement at photospheric level is covered with extreme precision by the 8 channels Vector Magnetograph (VM), completed by the DMOF in the low chromosphere and the UV channel of the giant, externally occulted, coronagraph (LCI of SuperASPIICS or CUSP) in the corona.

Elemental composition of plasma, temperature, velocities and densities in the transition region and corona are both addressed by the 2D UltraViolet Imaging Spectrometer (UVIS), the Extreme ultraviolet Diagnostic

Spectrometer (EDS) and the EUV and XUV Imagers (EUXI).

CMEs and Flares have imagers (SUAVE and the Heliospheric Large FOV Imager, HLI) and the High Energy Burst Spectrometers (HEBS) with Hard X-rays and gamma-rays unprecedented coverage of 10 keV to 600 MeV.

Solar variability, total and spectral, but also in other possible parameters to invent, like the solar shape, are covered by PREMOS II, STIP and SUAVE instruments.

Solar eclipses were, up to now, rare opportunities to access the inner corona since the scattering depends directly of the distance between the observer and the occulter. By using formation flying between two satellites 375 m apart, (occulting disk of 3.5 m on main satellite), a giant externally occulted coronagraph is built, accessing the very near-limb of the Sun at 1.01 solar radii and with high resolution. Unique measurements are possible from the visible Fe XIV line, IR Fe XIII and UV Lyman series and O VI.

Finally, 3 oscillation instruments allow to investigate, on one part, and with unprecedented performances, the deep interior for g-modes search with SUAVE (FUV imaging — variability and climate — and possible limb oscillations in the FUV) and with the GOLF-NG, and the convective zone for local helioseismology with the Dual Magneto Optical Filter (DMOF). These instruments have been detailed already (see Damé et al., 2013, for SUAVE for example). Cost constrains on National Agencies may however preclude their realisation if a bartering is to be done between extreme coronagraphy and oscillations.

To ease the life of Sun centered instruments (helioseismology, variability) these small instruments could be mounted on a Hexapod pointing platform. Again, this is an expertise of ESA (the Hexapod platform for Sage III on the Space Station was provided by ESA to NASA as a bartering for the Payload Adapter place for instruments on the Space Station) and the required signal to guide the Hexapod can directly come from the pointing telescope of SUAVE (alike the guiding telescope of SODISM on the CNES PICARD mission that is driving the microsatellite platform).

A mission lifetime of 3 years could be realistically anticipated in the first instance, but with hardware and consumables sized for a 6 to 12 years mission, consistent with a solar maximum mission observing the solar cycle 25, and an extended mission observing its decline.

The briefly outlined HiRISE concept could provide unique possibilities to do optical remote sensing observations of the Sun with unprecedented spatial resolution at scales below 20 km in images obtained in various wavelength bands. With the recent Hinode, SDO and IRIS revelations of fine structures existing in the corona it is obvious that coronal imaging is crucial to put the filamentary structures observed in the solar wind, coronal loops and inner heliosphere in their proper solar context.

An integrated ensemble of optical instruments would be visioned which may be combined in several packages involving large teams of scientists. Emphasis is put here on the scientific requirements and the presentation of feasible and proven designs to achieve them. All the imagers, beside the very high resolution of the interferometer, aim at high spatial (0.5 arcsec) and temporal (< 1 s) resolution, to reveal the context of the small-scale dynamical processes in the atmosphere and to study the rapid changes in morphology associated with transition region and coronal magnetic activity. Critical issues like heat ingress into the telescopes, aperture locations, mechanical structures of the instruments, would be evaluated as part of a future feasibility study and proven solution implemented, for example in the CNES PICARD microsatellite programme (Carbon-Carbon structure, etc.).

4. Potential Scientific Model Payload Instruments

4.1 Scientific Payload Concept

The dynamics of the chromosphere and corona is controlled by the emerging ubiquitous magnetic field. The plasma dynamics in each magnetic thread is believed to be linked to the formation of filaments, each one being dynamic on its own, in a non-equilibrium state. Mechanisms sustaining these dynamics, their manifestation in oscillations or waves (Alfvén or magneto-acoustic), require both very high-cadence, multispectral observations, and high resolution. Combining ultrahigh resolution and coronagraphy one could achieve:

• resolution (0.02”), chromosphere-corona interface characterization with a 1.4 m UV-FUV telescope equivalent (3 x 500 mm telescopes, independent or combined) and 3D imaging spectro-polarimetry;

• eclipse-like extreme coronagraphy of inner corona (up to 1.01 R_{Sun}) in vis., UV, NIR by Formation Flying between 2 satellites 375 m apart: Fe XIV, He I D3 & 1083, Fe XIII 1075 & 79, Lyman series & O VI;

• continuity, waves and oscillations, global and local magnetoseismology, EUV & XUV complementary imagers and spectrometers, TSI and photometers, and particles and magnetic fields experiments.

4.2 Payload Technology Developments

Major technical advances are contained in the three telescopes cophased and pointed system — an endeavour made possible by the success of the several ESA, CNES and CNRS interferometry studies —, and in the new instruments development, what is indeed expected since breakthrough instrumentation is a prerequisite for outstanding scientific outcome.

The important technologies needed by the proposed interferometer concept include stable structures and a cophasing system (phase measure and control). These technologies have been breadboarded by LATMOS with an end-to-end test from solar observation to image reconstruction. These achievements secure the development of the interferometer as both system design and detailed implementation issues are mastered. Among other interesting issues are progresses made by the Turin group with Liquid-Crystal allowing to finely tune a narrow spectral range with polarization capabilities (SuperASPIICS instrument), and the new stable and long-duty (solar cycle) Lyman-Alpha telescope SUAVE now in a remarkably optimized off-axis configuration with SiC mirrors.

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5. Potential Mission Configuration and Profile

5.1. Potential Mission Profile Summary

HiRISE could achieve its impressive aims with a major mission scenario involving two satellites in formation flying 375 m apart at the L1 Lagrangian point. The main spacecraft uses a modified Herschel platform and the chaser spacecraft, forming a giant externally occulted coronagraph, a Herschel-like platform. Novelty would also be in state-of-the-art, new instruments, allowing kilometric resolution and reasonable mass and volume, like the SOLARNET interferometer. The numerous high technologies, new features of HiRISE, would lead to novel insights into how the Sun works from the interior to the outer corona and to the Earth. With orders of magnitude in spatial resolution but also in sensitivity (UV spectro-imaging,diameter oscillations, and more), HiRISE is seen to have the potential to resolve major open science questions in modern solar physics and to bring in a wide variety of important discoveries. For the first time an ultra-high resolution formation flying facility would address directly the key component in understanding the Sun: the magnetic field structuring. It is anticipated that one would resolve it in much smaller features to analyze thoroughly the Sun's magnetic activity on multiple scales: time variability, evolution and fine-scale structure of the dynamic chromosphere, transition region and corona, origin, confinement, acceleration and release of energy, heating of the chromosphere and corona. HiRISE would also complement the *in situ* observations of the Solar Probe Plus (SPP) and fly-by of Solar Orbiter and build upon HINODE, SDO and IRIS moderate spatial resolution observations.

5.2. Mission and Technology Spacecraft Challenges – Science Perspectives

The main technologies necessary for the formation flying of the HiRISE concept will be mature at the time of the phase A kick-off thanks to PRISMA and ASPIICS/PROBA-3 in orbit demonstration.

- In the frame of the PRISMA mission, Thales Alenia Space has already fully demonstrated the RF metrology and the associated formation control modes and software.
- The HiRISE formation flying needs have to be fully covered by an appropriate technology development plan, including but not exclusively the following R&D: i) RF Metrology; ii) Optical Lomngi & Lateral metrology; iii) mu-propulsion; iv) Formation flying avionics SW; v) Ka band high rate modulator.

The Formation Flying technologies are the principal technology developments required for the mission; they are already funded through either national, ESA TRP or GSTP actions, ensuring their availability for the HiRISE.

6. International Collaborations

HiRISE would serve a large community of more than 70 Co-Is in 15 countries around the world (cf. front cover for a subset of potential core team members). In addition, we would anticipate a very significant participation of non-EU institutes in this project (leading even up to 3 major instruments by Asian partners), the payload can be extremely ambitious gaining orders of magnitude on previous recent missions (HINODE, STEREO, SDO, Solar Probe) or on the ones to come (Solar Probe Plus or Solar Orbiter).

Russian colleagues from the Lebedev Institute would also contribute a major instrument. Resulting charge for European countries intending to provide payloads is therefore limited and reasonable (< 200 M€).

HiRISE at L1 Lagrange point will be also highly complementary to the NASA Solar Probe Plus mission to which it brings coronagraphy, coronal magnetometry and very high resolution in the upper chromosphere, transition zone and inner corona where most of the coronal heating physics is thought to happen through flux tubes convective motions, waves or magnetic reconnection of tangled magnetic field strands. HIRISE would builds upon our European competencies in EUV/XUV imaging and spectroscopy, would enhance global and local helioseismology measurements, use the revolution in high resolution made possible by interferometry, and add the breakthrough of formation flying to achieve close limb coronagraphic observations. Furthermore, continuity of observation at the L1 Lagrangian point could allow unprecedented new limb and velocity oscillations search for g-modes, to understand the magnetic origin of the solar activity leading, hopefully, to predictions for the coming decades.

In this White Paper we suggest to measure a wide range of key solar parameters (magnetic and velocity fields, particle energy spectrum, TSI, etc.) to determine what drives the local and global dynamics from the photosphere interconnecting to the outer solar atmosphere. The full science return can only be achieved by an L-class mission given the key element of the proposed unique formation flying. With a downgrade to an M-class mission, other scenarios with a narrower scope might become possible. One downgrade option that could be instigated would be, in the context of Voyage2050, to combine our ultra-high resolution suggestion (downgraded to M-class) with one or more missions in the fields of solar, heliospheric, magnetospheric, and ionospheric physics as described in other White Papers to this call. This would provide a Grand European Heliospheric Observatory that not only addresses major challenges in the Solar-Terrestrial physics discipline but provides rapid scientific advances in a holistic approach to science that underpins our European space weather requirements for decades to come.

ANNEX A

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