Magnetic Properties of the Solar Atmosphere

(SolmeX Cosmic Vision Mission)

2010 NRC Decadal Survey White Paper

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The structure and dynamics of the solar atmosphere is dominated by the magnetic field. Our current lack of measurements of the coronal magnetic field is a major drawback to advance our understanding of the solar atmosphere. It is now technologically feasible to overcome this observational gap and obtain comprehensive set of measurements of the magnetic field from the chromosphere to the outer corona through remote-sensing techniques over a multitude of spatial and temporal scales.

For each of the two ESA Cosmic Vision program calls for mission concepts, there has been a proposal submitted to achieve the first comprehensive set of measurements of the magnetic field in the upper atmosphere through spectro-polarimetic techniques. In order to provide to the NRC Decadal Survey a well-developed mission concept, this white paper will summarize the mission proposal being submitted to the 2010 ESA Cosmic Vision call entitled “Solar Magnetism Explorer – SolmeX”.

The specific science addressed by such an investigation includes the fundamental issues:

1. What determines the magnetic structure of the solar upper atmosphere?
2. What is the nature of the changes of the magnetic field over the solar cycle?
3. What drives large-scale coronal disruptions such as flares and coronal mass ejections?
4. How do magnetic processes drive the dynamics and heating of the outer atmosphere?
5. How is the magnetic field coupling the whole solar atmosphere, from the photosphere to the outer corona?

1 Structure of the coronal magnetic field

i. What is the magnetic structure of the corona on large scales?

During solar minimum the large-scale corona appears dipole-like. The polar coronal holes show a super-radial expansion, i.e., they expand faster than radial rays roughly following the edges of the helmet streamers at lower latitudes. However, in-situ observations suggest a more radial expansion, and radial rays are visible seemingly poking through the boundary between coronal hole and the quiet corona (Woo et al. 1999).

Coronagraphic observations of the magnetic field of the large-scale corona (e.g. of the edges of coronal holes and of helmet streamers) are necessary to understand the connection between the corona and solar wind.

ii. What is the internal magnetic structure of coronal loops?

Imaging observations show in great detail loop reaching high into the corona, with heights of 10% of the solar radius or more. It is generally accepted that these outline magnetic field lines which are loaded with hot plasma as a consequence of the coronal heating process. However, while the coronal loop cross sections appear constant in observations, they should expand upwards according to the decrease of magnetic field strength with height. Furthermore the internal magnetic structure of coronal loops is unknown, e.g., their twist is an open issue.

These issues can be addressed by simultaneous measurement of the direction of magnetic field in a coronal loop and the structure of the coronal loop in EUV and visible light. This will provide results on the alignment of the observed structures with the magnetic field.

iii. What is the magnetic structure of the quiet Sun network?
On smaller scales of the order of 1Mm in the chromosphere and the transition region to the corona the Sun is highly structures and very dynamic. A multitude of small-scale short-lived phenomena can be seen, such as spicules, fibrils, explosive events, etc.

Spicules have been extensively studied with Hinode in chromospheric emission of Ca II. Indications of Alfven waves have been found to travel along the Spicules (De Pontieu et al. 2007). These conclusions are based on intensity images alone, and no reliable measurements of the magnetic field in spicules exist. Extending to somewhat higher temperatures, there are small transition region loops found crossing the chromospheric network. These are puzzling because there seems to be no connection from these small network loops to the underlying photosphere (Feldman et al. 2001).

To address these questions one must measure the magnetic field in lines formed in the chromosphere and the transition region. Measurements of the magnetic field the MgII k (279.6 nm) and in CIV (154.8 nm) provide magnetic information on spicules on the disk and above the limb as well as for small transition region loops above the chromospheric network.

2 The corona within the solar cycle

i. How does the magnetic field change in the corona on a global scale?

It has been known from eclipse images that the appearance of the corona changes dramatically within the 11-year solar cycle, i.e., with the cyclic change of the sunspot number. While having a dipole-like structure during minimum activity, the corona becomes very complex during maximum activity manifest through the numerous helmet streamers distributed all over the Sun.

During solar minimum coronal holes appear mainly near the poles, while during maximum activity smaller coronal holes appear at lower latitudes. These leave different imprints in the solar wind which are not understood. Coronagraphic polarimetric measurements of large-scale coronal structures over the solar cycle will reveal the differences in magnetic structure between minimum and maximum conditions through long-term observation over at least half a solar cycle, i.e., 6 years.

3 Large coronal disruptions

i. How is the magnetic field changing during large disruptions such as flares and CMEs?

In large disruptions of the corona, huge amounts of magnetic energy are converted into thermal energy and kinetic energy. The associated heating and acceleration process through magnetic reconnection are still poorly understood, and even the change of the magnetic structures is not well constrained. Currently extrapolations of the magnetic field from the surface level are used to investigate the change of the free energy of the magnetic field. However, during dynamic events the assumptions of these extrapolations break down. Thus there is dire need for measurements of the coronal magnetic field in the course of the disruption. Simultaneous measurements of the magnetic field in the chromosphere, the transition region and the corona itself are necessary to address this problem. This provides vital data to constrain models and extrapolations of the magnetic field during the disruption and will identify regions of particular high potential for magnetic reconnection.

ii. What is the magnetic structure of a CME during an eruption?

Once a coronal mass ejection (CME) lifts of, it expands and through this some CMEs reveal their internal structure. Our current information is based on intensity images and this no information on the magnetic field is available.

This is unfortunate as different models for CME eruption make detailed predictions on their internal magnetic structure. As these CMEs often lift off with high speeds of the order of 1000 km/s, they cross a field-of-view of one solar radius in 10 minutes, which sets minimum requirements for the observations.

High-cadence infrared coronagraphic spectro-polarimetry can provide both the intensity structure of CMEs and the magnetic field vector. By this the different CME models can be tested and the physics of the CME eruption can be resolved.

4 Magnetic driving of coronal dynamics

i. How does the plasma respond to heating in current sheets?

In general the magnetic field will not be irrotational, which is the same as to say that currents are present, which are often organized in thin sheets. In-situ observations show these directly, e.g., the heliospheric current sheet, but they can also be found on small scales of 1Mm in the low atmosphere of the Sun (Solanki et al. 2003). According to theory they should exist on all scales, most prominently during reconnection events, when magnetic energy is converted to thermal and kinetic energy. While extensively studied theoretically, there are virtually no observations of current sheets in the upper solar atmosphere, simply because of the lack of magnetic field measurements. Many processes are believed to be based on current sheet reconnection, e.g. explosive events (Innes et al. 1997), but the link to the magnetic field structure is missing.

Spectro-polarimetric observations on all accessible scales combined with the measurement of Doppler shifts and changes in observed structures will determine the link between current dissipation during reconnection and the response of the plasma.

ii. Is wave action or field line braiding the dominant heating agent?

Certainly the driver of coronal dynamics and heating is to be found in the solar photosphere. However the agent to transport the energy out into the corona, against a temperature gradient, is not yet identified.

The convective motions of solar granulation shuffle around the magnetic field and through this will induce currents in the corona which are dissipated. This field line braiding (Parker 1972) indeed produces a hot corona in numerical models (Gudiksen & Nordlund 2002) which are consistent with observed spectral properties (Peter et al. 2004). Depending on the speed of the driver, the same process could also induce waves, which propagate upwards and then heat the corona through their dissipation. In order to distinguish between these processes, polarimetric observations in the chromosphere, transition region and corona with a cadence faster than the granular convective time (5 min) and sub-granular resolution (order 1”) are required.

iii. Which are the source regions of the wind?

Globally, fast solar wind streams are known to originate from large coronal holes. However, their detailed source regions in the lower corona and magnetic network remain poorly determined. In particular this is due to the lack of direct measurements of the coronal magnetic field in the chromosphere and the transition region to the corona, where the wind is initially accelerated (Tu et al. 2005). Probably all types of solar wind streams might ultimately originate through the interaction of coronal loops and open field regions, in which case the loops should open up intermittently to release plasma into the corona and solar wind. The combination of imaging of coronal plasma and spectro-polarimetric measurements of the magnetic field is required to determine the magnetic structure of the solar wind source region.

iv. What drives the wind in the upper corona?

Fast solar wind streams are permeated and dominated by large-amplitude Alfven waves, which may be generated by foot-point motions in the photosphere and magnetic reconnection in the chromospheric network. In the upper corona these waves can interact with the plasma, e.g., through the ion-cyclotron resonance, which leads to an asymmetric velocity distribution of the ions (Kohl et al. 1998).

Measurement of the magnetic field in the upper corona (where the temperature anisotropies are observed) will identify the gyration frequencies as a function of distance and determine the heating and acceleration of the wind on larger scales. This simultaneous spectroscopic analysis of the wind speed, e.g. through Doppler dimming, and of the magnetic field through EUV and IR spectro-polarimetry will constrain the models which are currently built on numerous assumptions.

5 Magnetic coupling through atmosphere

i. How does the atmosphere couple across the plasma beta=1 layer?

The plasma beta is the ratio of the thermal energy density of the gas to the energy density of the magnetic field, and it happens that beta is about unity somewhere in the upper chromosphere. Below, where beta>1, the plasma dominates the magnetic field and can push the field lines around. The situation is opposite in the corona, where beta<1.

Thus the upper chromosphere is of particular interest for plasma physics. Waves can convert from one mode to another resulting in different oscillatory behavior below and above beta~1 (e.g., McIntosh & Judge 2001). It is also unclear how the chromosphere and the transition region to the corona are magnetically connected through this region (Wikstøl et al. 1998). Spicules are among the most prominent features related to the beta~1 region still awaiting a conclusive explanation (De Pontieu et al. 2007). Simultaneous spectro-polarimetric observations of the magnetic field in the chromosphere and transition region will resolve the issue of magnetic coupling in this region.

ii. How are coronal structures rooted to the surface?

Certainly all structures in the corona have to be rooted on the solar surface. As soon as a structure detaches from the solar surface, it lifts off - as impressively seen during CMEs. Because of the exponential drop of the gas pressure with height the magnetic structures have to expand and ultimately fill the whole volume of the corona, while on the surface they are concentrated in small regions. As only a small fraction of the magnetic flux in the photosphere is connected to the corona, the important question is which parts of the surface are connected to which structures in the corona and how the coronal structures are driven from below. Answering these questions requires measurement of the magnetic field not only in the photosphere, but also in the chromosphere and low corona in order to guide and constrain models and extrapolations of the magnetic field into the corona. This involves measurements of the magnetic field on all scales, from small magnetic patches on the surface to large-scale structures observed with coronagraphs.

SolmeX Observational Strategy

SolmeX instruments will measure the polarization of light from the chromosphere and the corona, on-disk as well as off-limb, from space. Thus they will provide a comprehensive set of measurements of coronal magnetic fields. The instrument suite comprises imaging as well as spectroscopic devices for coronagraphic observations above the limb as well as for measurements on the disk, namely:

Off-limb	(a)	VIRCOR (Visible light and IR coronagraph),
	(b)	CUSP (Coronal UV spectro-polarimeter),
On-disk	(c)	EIP (EUV imaging polarimeter),
	(d)	SUSP (Scanning UV spectro-polarimeter),
	(e)	ChroME (Chromospere magnetic explorer).

Magnetic field diagnostics: Zeeman effect and Hanle effect

The Zeeman effect is a manifestation of the interaction of the magnetic moment of the atom and the magnetic field. In the presence of a magnetic field spectral lines split into components with circular and linear polarization, depending on the angle between the line-of-sight and the magnetic field vector. The Zeeman effect is very prominent in the infrared (IR) as the splitting of the components increases with the wavelength squared.. Early attempts to measure the polarization in the transition region line CIV at 154.8 nm gave no conclusive results (UVSP on the Solar Maximum Mission launched in 1980; cf. Lites 2001). The most recent attempt with the SUMI rocket (Summer 2010) unfortunately had technical problems.

The *Hanle effect* modifies the linear polarization in the presence of a magnetic field. Excitation through anisotropic radiation can induce linear polarization of atomic levels and by this of the resulting emission. Quantum coherence causes the magnetic field to modify this linear polarization and by this imprints information on its strength and orientation. Depending on the scattering geometry, i.e., 90 degree scattering above limb or forward scattering in front of the disk, the modification consists in a reduction or enhancement of the linear polarization amplitude and in a rotation of the direction of linear polarization. At higher field strengths the Hanle effect saturates and is sensitive to the field orientation only.

As the Hanle effect is sensitive to weaker magnetic fields than the Zeeman effect, the diagnostics of these two effects is complementary

The SolmeX Science, Instrument and Mission design are presented in the following tables:

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vis:† ~ 400 nm</td><td>Fe X (17.4 nm)</td><td>120 – 150 nm
incl, Ly-α, C IV</td><td>Mg II (279 nm)
Fe I (525 nm)</td></tr>
<tr><td>field of view</td><td>> 1 R_{Sun}</td><td>> 2 R_{Sun}</td><td>full disk</td><td>300”</td><td>300”</td></tr>
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<tr><td>image sequence *</td><td>?? s (n-p)
30 min (pol)</td><td>30 s</td><td>10 s (n-p)
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</table>

† visible: for observations of the K-corona * image sequence: (n-p): non-polarimetric, (pol): polarimetric mode

spectral lines or band	Ly-α, β, γ O IV (103 nm)	Fe XIII 1.07 μm vis: ~ 400 nm	Fe X (17.4 nm)	120nm–150 nm incl, Ly-α, C IV	Mg II (279 nm) Fe I (525 nm)

data rate	150	300	550	300	700
aperture	25 x 30 cm^2	⌀ 20 cm	⌀ 28 cm	15 x 10 cm^2	⌀ 25 cm
dimension cm^3	180 x 60 x 30	180 x 50 x 25	100 x 30 x 30	160 x 50 x 40	150 x 45 x 50
mass kg	70	60	40	68	52
power W	30	50	50	25	55

Mission Design

Launch Vehicle	Soyuz-Fregat 2b (TBC)
Orbit	Large-amplitude Halo orbit at Sun-Earth Lagrange Point 1 (L1)
Satellite System	
Satellite System Concept	Two-spacecraft formation, *Coronagraph Spacecraft* and *Occulter Spacecraft* at 100-m separation
Attitude Stabilization	3-axis stabilized, sun-pointing
Attitude Control	RPE of Line of Sight < 1 arcsec in 15 minutes
Payload Telemetry Rate, Data Volume	900 kbit/s, 78 Gbit/day
Mass Memory	100 Gbyte
Telecommunications	X-band, 3 Mbit/s telemetry rate, 8 hours/day
Power/Energy	1 kW, no eclipse
Propulsion	Hydrazine (AOC), Cold-gas (formation keeping)
Mass Budget	1400 kg with adapter, >> 20% margin wrt launcher capacity, including 260 kg payload mass with 20% margin
Ground System	35 m ground antenna, X band receive/transmit, 8 hours/day
Technology Developments	Formation keeping metrology (RF and optical): TRL = 3 (today), TRL = 9 (after Proba 3) Proportional thrusters: TRL = 4 (today), TRL = 9 (after GAIA)

The cost estimate for SolmeX is still under development at the time these NRC white papers are due. The cost estimate of the predecessor to SolmeX, COMPASS (Coronal Magnetism, Plasma and Activity Studies from Space), are provided for reference.

COMPASS Cost Estimate (2008)

ROM Cost estimate	%	M€.
Pre-Implement. phase	2%	6.0
Industrial activities	50%	150.0
Launch services	13%	40.0
Ground Segment (MOC+SOC)	12%	36.0
ESA Internal Costs	11%	33.0
Contingency	11%	35.0
Cost to ESA	**100%**	**300.0**
Payload (20% margin))		300.0
Cost at Completion		**600.0**