Nature of Prominences and their role in Space Weather
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Scientific Programmes with India's National Large Solar Telescope and their contribution to Prominence Research

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Abstract. The primary objective of the 2-m National Large Solar Telescope (NLST) is to study the solar atmosphere with high spatial and spectral resolution. With an innovative optical design, NLST is an on-axis Gregorian telescope with a low number of optical elements and a high throughput. In addition, it is equipped with a high order adaptive optics system to produce close to diffraction limited performance.

NLST will address a large number of scientific questions with a focus on high resolution observations. With NLST, high spatial resolution observations of prominences will be possible in multiple spectral lines. Studies of magnetic fields, filament eruptions as a whole, and the dynamics of filaments on fine scales using high resolution observations will be some of the major areas of focus.

Keywords. Solar telescope, Solar magnetic fields, Solar observations, Solar prominences

1. Introduction

The Indian Institute of Astrophysics (IIA) has recently proposed a 2 m state-of-the-art National Large Solar Telescope (NLST) for carrying out high spatial and spectral observations of the Sun with a view to obtaining a better understanding of the fundamental nature of magnetic fields and other phenomena in the solar atmosphere. Observations have established that the solar magnetic field is structured in the form of flux tubes that can be as small as a few kilometers. Several numerical simulations indicate that crucial physical processes like vortex flows, dissipation of magnetic fields and the generation of magnetohydrodynamic (MHD) waves can occur efficiently on length scales even as small as 10 km (e.g. Vögler *et al.* 2005, Stein & Nordlund 2006, Shelyag *et al.* 2011). Such waves are likely candidates for transporting energy to the upper atmosphere of the Sun. Spatially resolved observations are, therefore, essential to shed light on the different physical processes involved. Unfortunately, even the largest current solar telescopes are limited by their apertures to resolve solar features to this level at visible wavelengths. On the global scale, the energy stored in magnetic fields is eventually dissipated in the higher layers of the solar atmosphere, for instance in the form of flares and coronal mass ejections (CMEs) that release energetic solar plasma into the interplanetary medium.

Currently the 1.5 m German GREGOR and the 1.6 m US New Solar Telescope (NST) in Tenerife and Big Bear respectively, are the largest international facilities for solar observations. The 4 m Advanced Technology Solar Telescope (ATST) will be commissioned around 2020. This has provided a window of opportunity for India to build a 2 m solar telescope in the next few years.

With an innovative optical design, NLST is a 3 mirror on-axis Gregorian telescope with a low number of optical elements (6 mirrors) to reduce the number of reflections and yield a high throughput with low polarization. It will be equipped with a high order adaptive optics package to produce close to diffraction limited performance (technical details on the telescope design and focal plane instruments can be found in Hasan *et al.* 2010 and Hasan 2012). In addition to the requirement of good angular resolution, a high photon throughput is also necessary for spectropolarimetric observations to accurately measure vector magnetic fields in the solar atmosphere with a good signal to noise ratio. With an aperture of 2 m, NLST will be able to resolve structures with sub-arc sec resolution in the solar atmosphere as well as carry out spectropolarimetry with a high time cadence. A novel feature of NLST is that it will also be possible to perform night time observations of stars.

2. Broad Scientific Objectives

NLST is envisaged as a versatile instrument that will enable a broad class of problems to be investigated, to shed light on the complex interaction of magnetic fields with plasma in the solar atmosphere. It is well known that the magnetic field plays a crucial role in modulating solar variability and activity. Understanding how magnetic fields are generated and maintained on the Sun is basic to understanding the origin and nature of solar cycle and variability, and to predict in advance its behaviour both on short and long time scales. Another key issue that NLST will address is to study magnetic coupling between the interior and solar atmosphere that involves an investigation of dynamical processes in magnetic elements that enable the transport of energy to the chromosphere and corona.

Other areas of focus include local helsioseimology, measurement of weak magnetic fields in the internetwork where a significant fraction of field is below 400 G (Khomenko *et al.* 2003), the thermal structure of the chromosphere, particularly cool pockets with temperatures as low as 3600 K (Solanki, Livingston & Ayres 1994); and energetic phenomena and activity. An important goal of NLST will be to observe the magnetic field and dynamic changes that occur during solar flares. NLST will also contribute towards a better understanding of CMEs by combining optical data with radio to determine the connection between the changes that occur at chromospheric layers through H_α observations and type III radio bursts during flares.

An important focus of NLST will be the study of quiescent and active prominences.

3. Scientific programmes related to Prominences

It is well known that prominences exhibit a range of morphology when viewed above the limb consisting of nearly horizontal threads in some cases and almost vertical threads in other instances (Mackay *et al.* 2010). The reason for this is still not fully understood. Presently there are very few observations of magnetic fields in prominences.

3.1. *Magnetic Field Measurements in Filaments*

Balasubramaniam *et al.* (2006) obtained simultaneous observations of a filament structure observed on April 7, 2003 with the Advanced Stokes Polarimeter (ASP, Elmore *et al.* 1992) in H_α, Mg I 517.27 nm and the Diffraction Limited Spectro-Polarimeter (DLSP, Sigwarth *et al.* 2001) in Fe I 630.15/630.25 nm. They inferred the 3-D magnetic geometry, using linear force-free reconstruction based on the line of sight measurements of the magnetic field. They concluded that the filament material is located in regions where

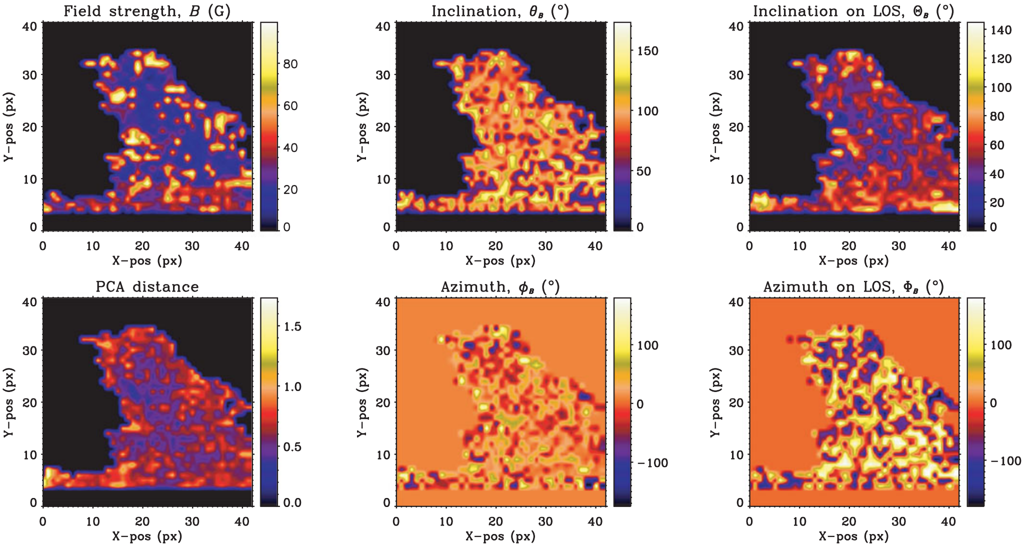

Figure 1. Magnetic map of a prominence observed on May 25, 2002 using the Dunn Solar Telescope (DST) at NSO derived from a PCA inversion of the four Stokes profiles of the He I D3 line. Both geometries of the field, respectively, in the reference frame of the local vertical, (θ_B, ϕ_B), and in the reference frame of the LOS, (Θ_B, Φ_B), are presented (from Casini *et al.* 2003).

the chromospheric field dips, similar to the Kippenhahn-Schlüter model (Kippenhahn & Schlüter 1957).

Figure (1) shows the magnetic map of a prominence observed on May 25, 2002 using the Dunn Solar Telescope (DST) derived from inversion of the four Stokes profiles of the He I D3 line (Casini *et al.* 2003). Vector magnetic fields were mapped down to the chromospheric limb. The analysis indicates that the average magnetic field in prominences

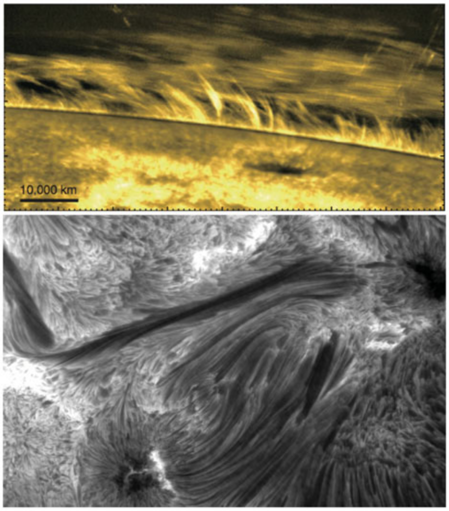

Figure 2. Upper panel: Thin threads in an active region prominence seen in Ca II H. The image was obtained with Hinode/SOT on 2006 November 9 (Okamoto *et al.* 2007). Lower panel: Thin threads of an active region filament seen in H_α. The image was obtained from the Swedish 1 m Solar Telescope on 2003 August 22, with a field of view of 83000 × 56000 km (from Lin 2011).

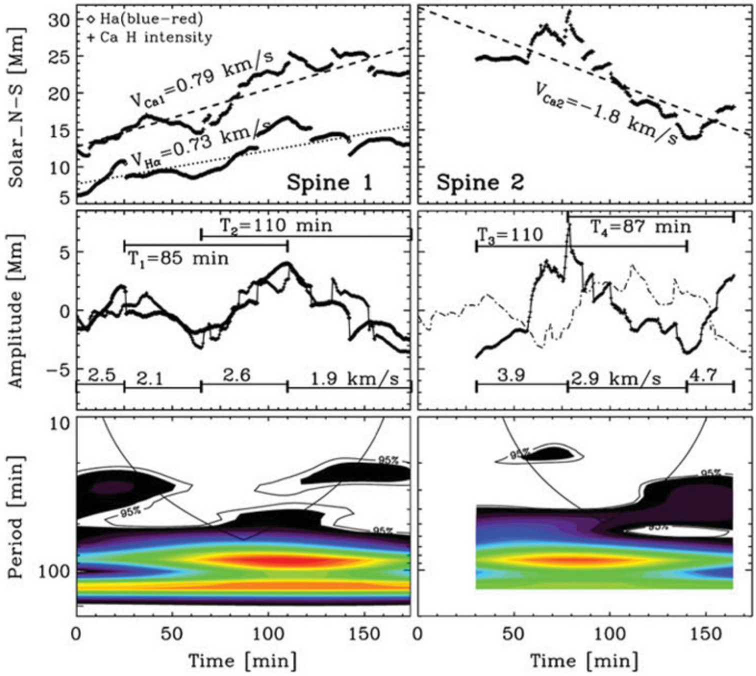

Figure 3. Quiescent filament observed in H_α by Hinode/SOT. Top panel: time evolution of two spine structures in Doppler and Ca II H intensity. Middle panel: oscillatory pattern of the two spine structures. Bottom panel: wavelet diagram of the oscillations of the two spines structures. (from Ning *et al.* 2009)

is mostly horizontal and varies between 10 and 20 G, thus confirming previous findings. However, these maps show that fields significantly stronger than average, even as large as 60 or 70 G, can often be found in clearly organized plasma structures of the prominence. NLST will routinely provide vector magnetic maps in prominences with higher accuracy.

3.2. *Fine Structure*

High resolution observations indicate the presence of fine structure down to the resolution limit of present day instruments (typically 100 km). Very thin dark fibrils visible along the spine of a quiescent prominence are seen as short structures inclined to the filament axis. Longer fibrils can be seen within the barbs or connecting various parts of the filament body. Figure (2) shows thin threads in an active region prominence in (a) Ca II H (Okamoto *et al.* 2007) as seen with Hinode (top panel), and (b) H_α (Lin 2011) using the 1 m Swedish Vacuum Solar Telescope. NLST, with its higher resolution, will be in a better position to study in greater detail the nature of the fine threads that make up spines, barbs and ends.

3.3. *Oscillations & Dynamics*

High resolutions observations (from the ground as well as space) reveal the presence of oscillatory motions in individual thin filaments. Small amplitude oscillations with velocity amplitudes 0.13 km s^{-1} in filaments are detected as periodic variations in line-of-sight velocity, line intensity, line width, as well as spatial displacement (swaying) of the threads. A range of oscillatory periods have been reported ranging from very short periods $\leqslant$1 min, short periods 1- 20 min, intermediate periods 20 - 40 min, and long periods 40 -100 min (Lin 2011). Ning *et al.* (2009) examined oscillations in two spine structures of a quiescent

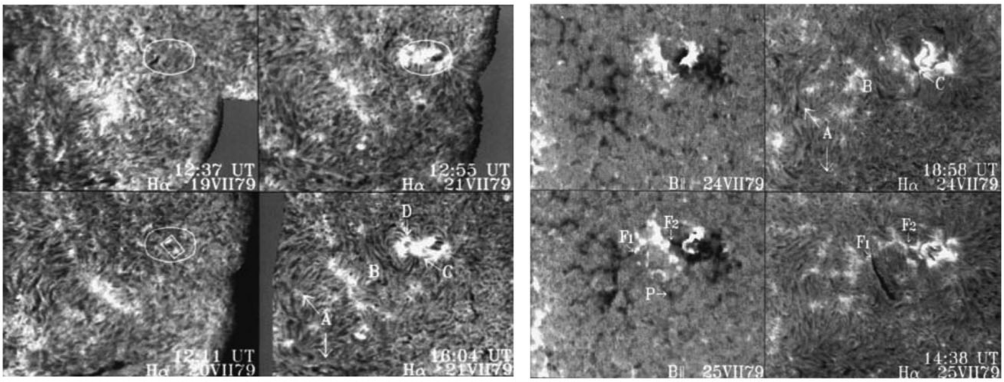

Figure 4. H_α image (right) and magnetogram (left) showing the final stages of the formation of an Intermediate Filament. The Intermediate Filament forms on the 25th July after flux convergence and cancellation occur at F1 in the bottom right panel (from Gaizauskas *et al.* 1997)

prominence. Figure (3) shows the time evolution of the H_α Doppler and Ca II H intensity using Hinode observations.

3.4. *Formation of filament channels*

Currently, there are two scenarios related to the filament channel (FC) formation. In the first one (Gaizauskas *et al.* 1997, Wang & Muglach 2007) channel formation takes place through surface motions acting on pre-existing fields. Figure (4) depicts the early stages (left panel) in the formation of an Intermediate Filament between an old remnant region (bright plages A & B in bottom right images) and an emerging activity complex (inside the oval).

The second scenario (Lites & Low 1997 and Okamoto *et al.* 2008) involves the emergence of a sheared flux rope that either replaces a pre-existing filament or reconnects with this filament. Figure (5) shows a time series of Hinode SP data to illustrate this phenomenon.

3.5. *Eruption & Disappearance of filaments*

STEREO/EUVI 304 Å observations of prominences show a helical twist in the spine during eruption (Joshi & Srivastava 2011). During eruption, the prominence exhibits non-radial motions. The non-radial motion and helical twist in spines can be used to determine the propagation dynamics of prominences. These results show that the acceleration of prominences is higher in the prominence leg where these two forces act in the same direction, and lower in the leg where they act in opposite directions. NLST will be able to carry out studies of the initiation of filament eruption or disappearance. It will carry out observations of filaments prior to their activation and identify some of the precursors.

4. Prominence Studies with NLST

Observations of prominences are ideally suited for a large aperture solar telescope such as NLST. In order to detect weak fields in quiescent prominences, a high polarimetric sensitivity with a good signal to noise is necessary. The aim is to map the vector magnetic field in the photosphere and the chromosphere accurately with high spatial resolution and high time cadence to study a range of dynamical processes. This will be carried out principally using a spectropolarimeter using multiple spectral lines simultaneously.

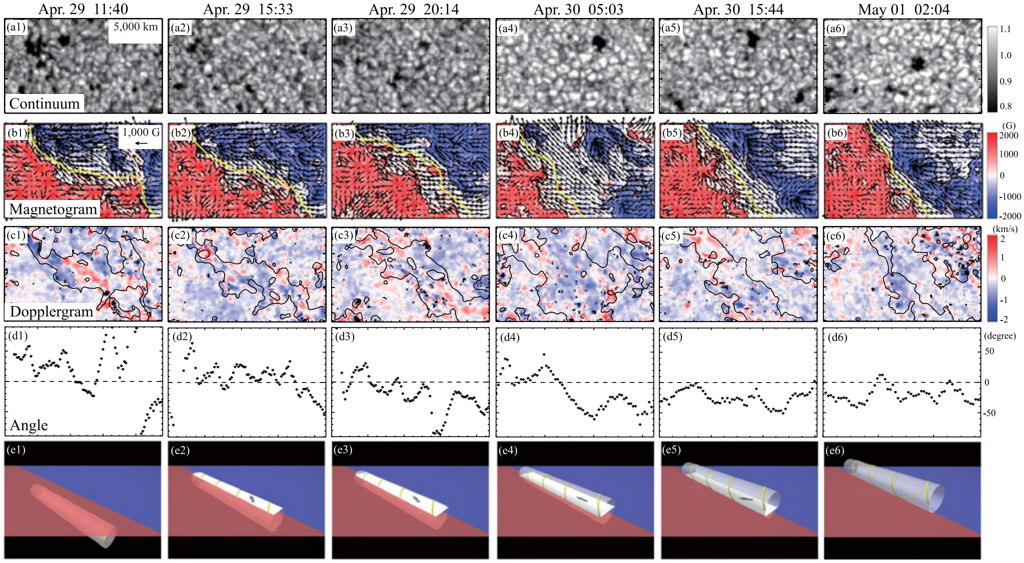

Figure 5. Time series of Hinode SP data. The field of view is 32" × 19". The red (blue) region indicates the plage (sunspot side) on the photosphere. The white tube is a helical flux rope. The yellow line shows a magnetic field line on the surface of the flux tube. Black arrows indicate the orientation of horizontal magnetic fields of this rope crossing with the photosphere (from Okamoto *et al.* 2008)

This instrument will seek to achieve a polarimetric accuracy better than 5 $\times 10^{-4}$, a wavelength coverage from 380 nm to 2.5 μ and low instrumental polarization ($<$ 1% before modulation and $<$ 10% before demodulation).

In addition, NLST will carry out high resolution 2-D observations of Doppler shifts required for carrying out prominence seismology investigations that seek to accurately determine physical conditions in prominences as well as the role of barbs in the evolution of filaments.

Presently, there are very few observations of the formation of filament channels. NLST will seek to examine FC formation in action regions using high cadence observations along with combined high resolution H_α and line of sight magnetic field observations.

5. Current Status

After four years of site characterization, two superb sites in the Ladakh region of Jammu & Kashmir, India have been located. A detailed project report has been submitted to the Indian Government and formal approval is awaited. Fabrication of NLST is expected to begin in 2014, with first light in 2018. An international consortium has been identified for fabricating the telescope. The backend instruments will be made indigenously.

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