

## Contents

## A. Motivation and Goals

Recent progress in solar instrumentation enabled us to peer more sharply than ever before into the solar chromosphere. This is the relatively thin (few thousand kilometers) atmospheric layer between the photosphere and corona. With increasingly finer resolution, the solar chromosphere shows an even richer ceaselessly changing character with small-scale energetic events occurring constantly all over the solar surface (Fig. ??). These events with their small-scale energy release are expected to hold the key to unlocking the mystery of chromospheric and coronal heating (??). Such chromospheric activity is thought to be the result of the relentlessly changing photospheric magnetic field driven by turbulent solar flows.

**Our Big Bear Solar Observatory (BBSO) team proposes a sharply focused study to explore the connection between chromospheric active features and photospheric dynamics taking advantage of the 1.6 m clear aperture New Solar Telescope (NST) in BBSO.**

Our goal here is to advance our understanding of how a variety of chromospheric events originate and to explore coupling between the photosphere and chromosphere. These events include spicules, rapid blue shifted events (RBEs or spicules II), anemone jets as well as tiny intergranular jets recently discovered using BBSO's NST (see Section ??). In particular we will constrain the driving mechanisms of chromospheric upflows.

Our goal will be achieved by analyzing high resolution NST, Hinode, and SDO data for coronal holes (CHs) and quiet Sun areas.

**Task 1.** Studies of chromospheric jet properties (such as velocities in association w/ the magnetic field and time evolution)

**Task 2.** Studies of chromospheric response to photospheric dynamics (e.g., bright point sudden horizontal acceleration, appearance/disappearance, collision, etc)

**Task 3.** One of the major goals of this research plan is to organize several joint campaigns between NST, Hinode and SDO. We believe that these joint observations and data analysis should be one of the major strengths of the NASA LWS focus science team (FST).

Success of the FST, to which this proposal is submitted, depends on both the effectiveness of each individual team member and the collaboration within the

team. The PI and Co-I of this proposal have previously worked in two successful LWS teams. We believe that our research plan, data and expertise will uniquely contribute to the success of the "jets" focus team (see Figure ??).

First, the NST is the largest aperture (1.6 m) solar telescope in the world (see Sec. ??) and is one of the only two ground based solar observatories in the USA (along with the National Solar Observatory) capable of routinely providing state-of-the-art data. NST's unprecedented high spatial (0".1) and temporal (5-7s) resolution photospheric and chromospheric images corrected with high order adaptive optics (AO) and covering long time intervals (up to 3 uninterrupted hours) are unique and critical to the success of the team. As we will demonstrate later in the text, NST granulation images are superior to the existing similar data and, as such, they allow us to follow evolution of individual bright points (BPs) during long time intervals, possibilities not achievable, for example, with Hinode data (see NST-Hinode comparison in Fig. ??).

Second, the NST data that we will bring to the table, complemented with Hinode and SDO observations, define the uniqueness of our research interest: connecting photospheric dynamics to chromospheric activity. Our data will cover the photosphere and chromosphere, the spatial domain where the cross section of magnetic structures is very small and therefore, the highest spatial resolution is critical.

Third, there are a number of research groups composed of well-qualified experts exploring the linking chromospheric, transition region, and coronal upflow events depicted in the upper part of Figure ?. However, the connection between small-scale chromospheric activity and the underlying photospheric dynamics is less explored and not well-understood (see the spatial domain enclosed by a box in Fig. ?). The origin of various chromospheric features does not appear to be sufficiently addressed in the existing studies. For example, what drives the most prominent flows, now known as RBEs, which are thought to be significantly contributing into coronal heating process? Is it magnetic reconnection or waves? It appears that there is no definitive answer to this simple question.

Up until now this topic was mainly represented by occasional research papers (e.g., ?) and for a good reason. To address the photosphere-chromosphere coupling in all detail one needs simultaneous high spa-

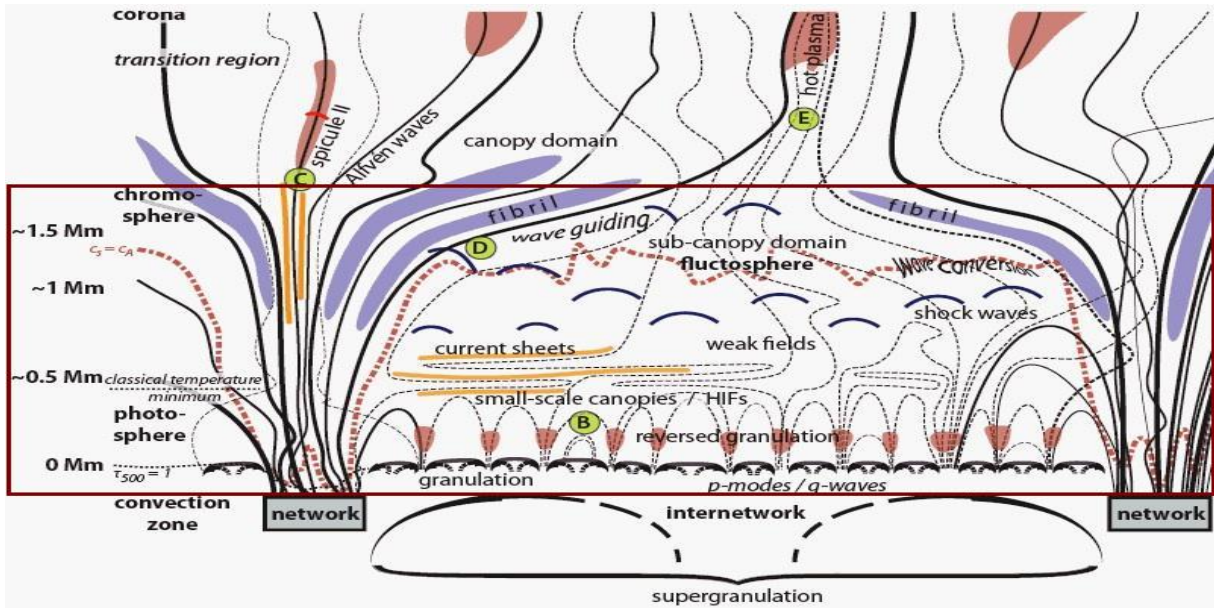


Fig. 1.— Schematic, simplified picture of the solar chromosphere (adopted from ?). Interplay between a hierarchy of turbulent surface flows and embedded magnetic fields creates a complex layer, with shocks and plasma upflows (jets) directly related to coronal heating. The boxed region schematically depicted here is the focus of our effort and it is also the least understood. High resolution data will enable us to connect chromospheric dynamics (spicules, dynamic fibrils, rapid blue-shifted events, jets) with photospheric activity (magnetic network, evolution of photospheric bright points, peculiarities of their motion and interaction, converging and vortex flows of turbulent plasma, etc). (See the complete figure caption in ?).

tial and temporal resolution data. Another important factor (as we found out analyzing NST data sets) is the temporal coverage. Short (15-30 min) data sets, although valuable, are not sufficient when it comes to understanding of the nature and evolution of the network field and associated bright points, as well as linking them to chromospheric activity.

NST has been actively collecting data since Summer 2009. In 2010 we expanded our instrumentation base and now simultaneously observe solar surface with broad (TiO, G-band) and narrow (H $\alpha$ ) filter imagers as well as Infra-Red Magnetograph (see Sec. ??). All recorded images fed by light corrected by high order adaptive optics. During the period of this proposal, we will continue to acquire data with the NST. Joint observation campaigns could be and will be set in the framework of the focus team collaboration. These campaigns will extend the range of data available for analysis by the whole LWS team.

## A1. Proposed Contributions to the Focus Team Effort

2010 NASA LWS solicitation is seeking to create an efficient team that would attack problems related to the origin and dynamics of jets. The solicitation specifically states that “developing predictive models for the coupling of the chromosphere to corona requires a comprehensive understanding of the origins and dynamics of jets.” Jets may be playing an important role in the origin and properties of the solar wind. Also, “deep understanding of jets may also be critical for modeling the coupling of the corona to the wind”.

NASA defines the goal of this FST as “to advance our understanding of the origins, structure, and dynamics of chromospheric and coronal jets ...”. This proposal is therefore relevant to the NASA LWS solicitation since its main goal is to understand the origin of small scale chromospheric jets based on NST’s photospheric and chromospheric data augmented by Hinode and SDO missions. The potential contribution of the BBSO group to the LWS focused science team will include (see Figure ??):

1) Data sets. BBSO now operates its largest 1.6m

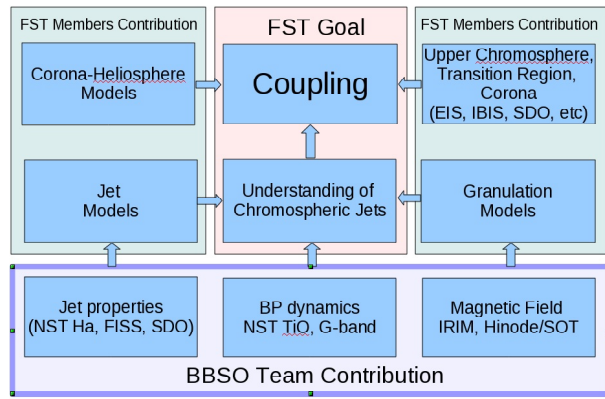


Fig. 2.— Contribution of BBSO team into the collective effort of the NASA’s LWS Focused Science Team (FST) “Solar jets”.

solar telescope, which provides unique high resolution photospheric and chromospheric images and magnetic field measurements. The focused team “jets” will most certainly benefit from these unique data sets.

II) Organizing joint campaigns between BBSO, Hinode and other observatories (depending on the team members).

III) Data analysis. BBSO group will perform data analysis and derive physical and statistical properties of jets and underlying magnetic fields. The results will be presented and discussed at team meetings and we expect that the team will also contribute to their scientific interpretation. The outcome of such discussions will be a more refined and focused research and/or plan for joint observations.

By combining results from various groups we will be able to make a substantial progress in understanding mass and energy transfer. For example, BBSO team will explore coupling between the photosphere and chromosphere, while other teams will address the link between the chromospheric and coronal upflows, and model the entire system.

IV) Results of statistical studies of observed intensity structures and magnetic fields can be compared to those derived from simulated data sets. Such comparative studies could lead to a significant improvement of existing MHD models.

The PI and Co-I of this proposal have the experience of previously working on two successful LWS FST teams and thus understand how the significant progress can be made during the semi-annual team meetings, where scientists from various fields of solar

physics are brought together to exchange ideas and start collaborative projects. Interaction with experts within the team may tailor our plans for the needs of the team. The above list presents only few obvious topics for a possible collaboration and certainly more realistic collaboration plan will be made after team members are known and the team is created.

## A2. Expected Significance and Broad Impact

As we will show below, NST data enable us to see details on the solar surface with unprecedented clarity as never seen before. Thus, we can expect knowledge that has escaped us, because of lower resolution of the existing data, to be revealed on the dynamics of small scale magnetic fields in the photosphere and the chromosphere.

This new knowledge may contribute to our understanding of how the Sun works (for example, jets could be found to be self-similar, i.e., active region and quiet Sun jets may be the same phenomena (from a morphological point of view) occurring on different spatial and time scale. Improved understanding of solar coronal heating may therefore be applied to other stars.

Since the NST’s first light, and especially, since the first images were taken with the adaptive optics system, many schools, magazines, and popular science websites expressed their interest in our data. We have created a pilot version of a NST gallery web page, where we present selected images and movies ([http://www.bbsu.njit.edu/nst\\_gallery.html](http://www.bbsu.njit.edu/nst_gallery.html)). We plan that in the future, the collection of images be accompanied by detailed annotations explaining in popular terms events and phenomena captured in the data. Bringing our data before the public will help to understand the world at large and will let teachers and students use state-of-the-art data in classroom work.

## A3. Team’s Experience and Expertise

Vasyl Yurchyshyn is PI of this proposal. His long experience in studies of solar active events (coronal mass ejections, flares, jets) make him the ideal person to lead the group effort.

Valentyna Abramenko is a funded Co-I and is an expert in the analysis of small-scale magnetic fields observed in active regions, quiet sun areas, and coronal holes.

Wenda Cao a non-funded Co-I of the project and he is leading the development of scientific instrumentation

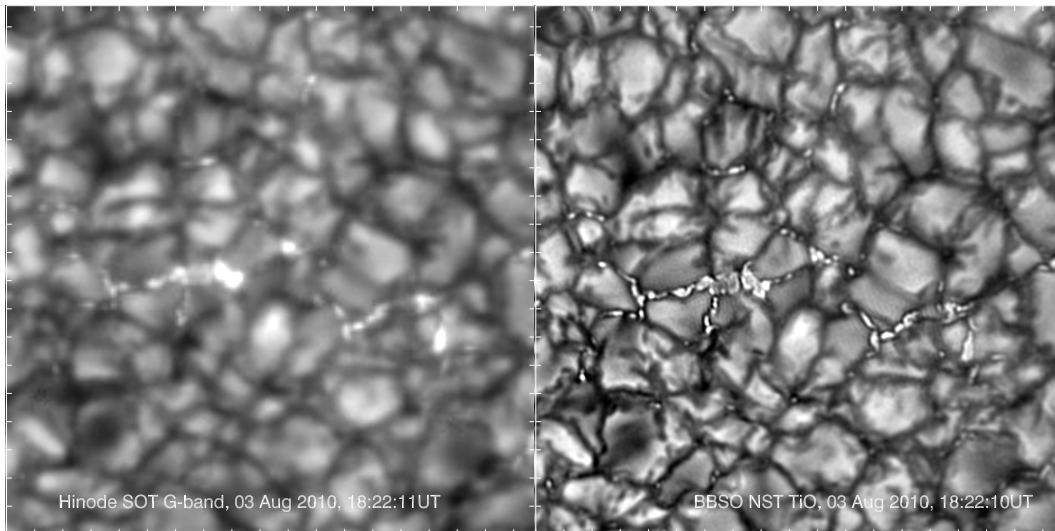


Fig. 3.— *NST instruments are now actively collecting data. Here we show a  $19'' \times 19''$  Hinode/SOT G-band (left) and NST TiO (right) image of the same area of the Sun acquired on Aug 3, 2010. Note one-to-one correspondence between G-band and TiO bright points. The NST image clearly displays several tight clusters of resolved bright points (BPs) near the center of the FOV, which are seen in the Hinode image as single bright patches. Meanwhile, there are indications that such tight clusters of various size are located at roots of chromospheric up flow events. The spatial and temporal resolution of the data allows us to track these individual BPs during their lifetime. (see e-version of the figure at <http://www.bbo.njit.edu/2010LWS>)*

of the NST, in particular, the InfraRed Imaging Magnetograph (IRIM) project (see below).

#### A4. Instruments Overview

The 1.6m, off-axis, clear aperture NST in BBSO (?) is in regular operation. NST's off-axis design was chosen principally because of its vastly reduced stray light, since there is no central obscuration, which would reduce the telescope's modulation transfer function, which is especially important at high spatial frequencies. The new telescope already offers a significant improvement in ground-based high angular resolution capabilities, and will substantially enhance efforts to understand the photosphere and the associated chromospheric dynamics.

The NST is configured as an off-axis Gregorian system consisting of a parabolic primary, prime focus field stop and heat reflector (heat-stop), elliptical secondary and diagonal flats (see more at [http://www.bbo.njit.edu/nst\\_instr.html](http://www.bbo.njit.edu/nst_instr.html)). The primary mirror (PM) is 1.7 m with a clear aperture of 1.6 m. The PM was figured to a final figure residual error of 16 nm rms by Steward Observatory Mirror Lab. The focal ratio of the PM is f/2.4, and the final ratio is f/52. The 100'' circular opening in the field stop defines a  $70'' \times 70''$  maximal square field of view of the NST. The light is further folded through the declination axis and then directed by the Coudé mirror down the polar axle. The working wavelength range covers 0.4 to 1.7  $\mu\text{m}$  in the Coudé Laboratory (two

floors beneath the telescope).

##### A4.1. Adaptive Optics System

A high-order adaptive optics (AO) system built in collaboration with the National Solar Observatory/Sacramento Peak is now operation in conjunction with the NST. The AO system incorporates a 97 actuator deformable mirror, a Shack-Hartmann wave front sensor with 76 subapertures, and an digital signal processor system. More details can be found in ?.

##### A4.2. KISIP Software for Speckle Reconstruction

The Kiepenheuer-Institut für Sonnenphysik's software package for speckle interferometry of adaptive optics corrected solar data (KISIP) is a post AO reconstruction algorithm allowing to achieve the diffraction limit of the telescope over a large field of view most of the observational time (?). The approach is based on Fourier phase reconstruction algorithms using either an extended Knox-Thompson or a triple correlation scheme. The code has been written in the C programming language and optimized for parallel processing for BBSO computers.

##### A4.3. Broadband and $H\alpha$ Filter Imagers

BBSO's Coudé Laboratory currently hosts three instruments, among them a broad and a narrow band imagers. The Broadband Filter Imager (BFI) allows one to observe the solar surface using either a TiO (706nm) or a G-band

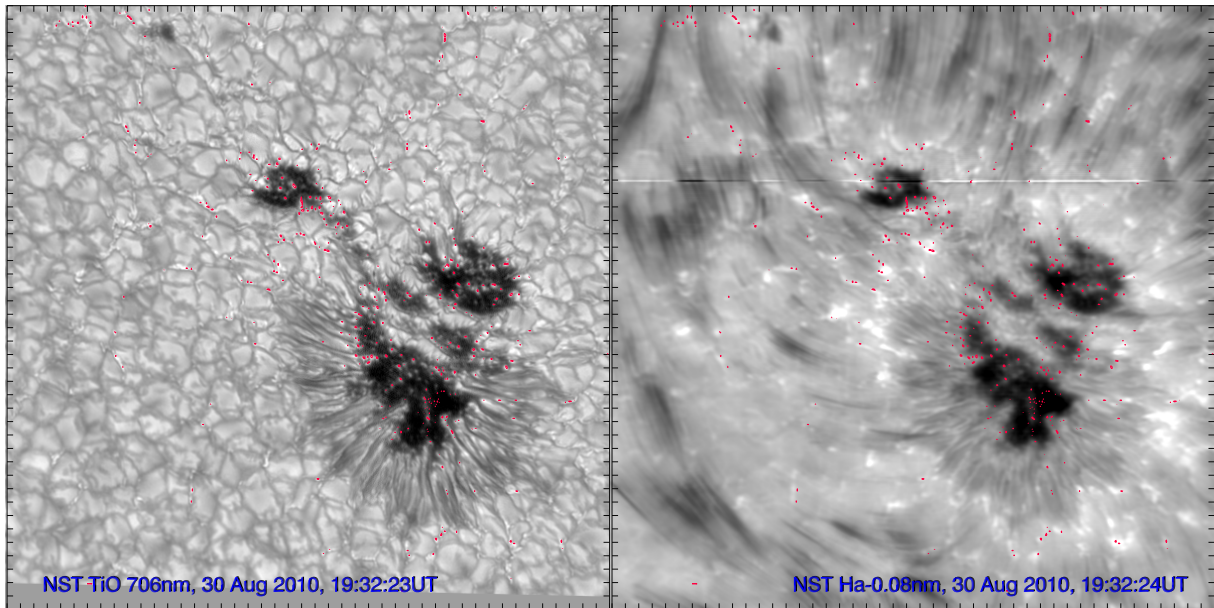


Fig. 4.— NOAA AR 1102 as seen through the TiO (left) and the off-band  $H\alpha$ -0.8Å (right) filters on Aug 30, 2010. The red dots mark locations of the most intense TiO BPs. The data shows excellent correspondence between the photospheric and  $H\alpha$  bright points, the latter being larger in size. The off-band  $H\alpha$  image shows numerous striations originating from the AR's plage fields (concentrations of BPs), which were identified as rapid blue-shifted events and they thought to be disk counterparts of spicules II. In case of quiet Sun regions, similar striations are rooted in network fields. Such simultaneous multiwavelength observations will allow us to reliably relate chromospheric jetting activity with photospheric dynamics such as rapid BP motions, collisions, appearance, etc. (<http://www.bbso.njit.edu/2010LWS>)

interference filter. In order to apply the speckle code, the data have to be taken in a succession of bursts of images. Each burst usually consists of 100 images taken at a rate of 15 frames per second. When observing in full resolution mode (2048×2048 pixels) the minimum time cadence is 15s, which can be reduced down to 7s by varying various parameters.

When using the TiO filter with a bandpass of 1nm centered at 706nm, the BFI instrument integrates radiation over all wavelength. Considering that the TiO band is very temperature sensitive and weak everywhere outside the sunspot, observations made with the TiO filter are only weakly dependent on the line depth (??). At the same time, it is expected that in dark and cool intergranular lanes, the TiO line depth slightly increases, thus increasing contrast of the BPs located there without affecting their peak intensity. It is accepted that the height of the TiO band formation is between 130 and 160km, which places it slightly higher than the G-band. Fig. ?? compares BPs as seen in G-band and TiO images. Disregarding the obvious difference in the spatial resolution, we would like to stress that all Hinode G-band BPs are seen in TiO images, moreover, their contrast in NST data is even higher. We therefore argue that TiO data are very well suitable for addressing temporal evolution of BP (appearance/disappearance) and their motions. We note that the intensity of BPs measured

from G-band and TiO images may be different, which can cause problems when performing comparative studies of, say, brightness oscillations.

The Narrow Band Imager (NFI) utilizes the  $H\alpha$  Zeiss Lyot filter with a bandpass of 0.25Å. Since the CCD sampling was set to match NST resolution at the blue side of the visible spectra, observations at longer wavelengths are somewhat over sampled. Therefore, the NFI data may be binned without losing spatial resolution, which also allows us to operate at a temporal cadence below 5 sec due to increased frame rate.

Our test showed that reduced size of the burst (e.g., 70 adaptive optics corrected images in one burst) and binning do not significantly affect the resulting speckle reconstructed images, so this mode of observations can be utilized in order to achieve higher temporal cadence.

The FOV of both imagers is 77 by 0.77", and the pixel scale is 0.0375" (0.075" in case of the binning mode). This pixel size is 2.9 times smaller than the Rayleigh diffraction limit of NST,  $\theta_1 = 1.22\lambda/D = 0.11" = 77$  km and 2.5 times smaller than the FWHM of a smallest resolved feature<sup>1</sup> ( $\theta_2 = 1.03\lambda/D = 65$  km).

<sup>1</sup>[http://www.telescope-optics.net/telescope\\_resolution.htm](http://www.telescope-optics.net/telescope_resolution.htm)

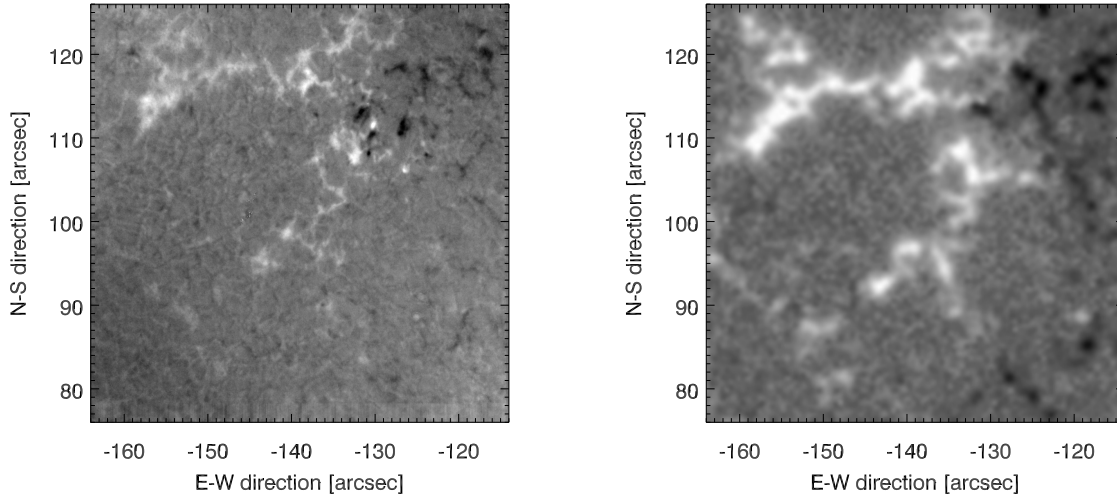


Fig. 5.— *IRIM* (left) and *SDO* (right) magnetograms of the same area recorded on Sept 13, 2010 near the disk center. Improving spatial resolution reveals that seemingly unipolar fields may be in fact much more complex, with tiny patches of opposite polarity encrusted into the unipolar network fields. These tiny magnetic elements may play essential role in generating chromospheric upflows.

#### A4.4. InfraRed Imaging Magnetograph

As a fast-emerging field, IR solar observations possess unique advantages: First, the Fried parameter, isoplanatic angle, and Greenwood time delay of the terrestrial atmosphere are all proportional to  $\lambda^{6/5}$  for the generally-assumed Kolmogorov turbulence, where  $\lambda$  is the wavelength. In the near IR, the median Fried parameter at BBSO is steady at a level of 24 cm, which is at least 4 times that in the visible<sup>2</sup>, under the same observing conditions<sup>3</sup>. Note that the Fried parameter characterizes seeing quality at the observation site: the bigger the better. Therefore, adaptive optics is much easier to implement in the IR.

Second, the Zeeman splitting is a function of  $g\lambda^2B$ , where  $B$  is magnetic field strength and  $g$  is Landé factor. Even a moderate magnetic field can cause full line splitting in the near IR, allowing magnetic field measurements with high sensitivity along with a separation of the magnetic flux into field strength and filling factor. Meanwhile, cross-talk between the circular polarization and linear polarization induced by oblique reflectors are considerably suppressed in the IR.

Finally, stray light from both the atmosphere and the telescope are strongly minimized in the IR compared to the visible. There are several advantages in using near IR data specific to the current study: i) the  $1.5\mu\text{m}$  spectral line, used by IRIM, forms deep in the photosphere, where magnetic structures are more confined, which will provide bet-

ter chances for them to be resolved; ii) high time cadence is essential, since small-scale magnetic features have short life time; iii) Zeeman splitting is larger in the near IR, so fields and their filling factors can be separated; iv) the terrestrial atmosphere is less turbulent at longer wavelengths making such field measurements more straightforward, and v) NST/IRIM makes our observational programs flexible so that any target can be measured as long as needed and when needed.

BBSO/NJIT has successfully developed several generations of near IR imaging instruments, but the most remarkable achievement is the development of the InfraRed Imaging Magnetograph (IRIM, ??) for BBSO's now-retired 0.65m telescope before it was dismantled for the installation of the NST. IRIM has been redesigned to outfit the NST and was successfully installed in the Coudé Lab in the Summer 2010. Fig. ?? shows the capability of IRIM at high spatial resolution.

This innovative filter-based spectro-polarimeter, based on a 2.5nm interference filter, a unique  $0.25\text{\AA}$  birefringent Lyot filter, and a Fabry-Pérot etalon, is capable of providing a bandpass as low as  $\sim 0.01\text{nm}$  over a FOV of  $50'' \times 50''$  in a telecentric configuration. Based on the unique advantages of the near IR window, and the most capable NST equipped with AO, IRIM will provide unprecedented solar spectro-polarimetry with high Zeeman sensitivity ( $10^{-4}$ ), diffraction limited resolution ( $0''.2$ ), and high cadence ( $\sim 1$  min for full Stokes profiles).

Even with a 24 cm isoplanatic patch, AO is essential for IRIM. We note that the Strehl ratio at 1.6m for the NST is about 0.7, which is easily large enough to allow diffrac-

<sup>2</sup>Fried parameter of 6 cm in the visible is large enough to resolve granulation, use it as a “guide star” and, thus, allow adaptive optics to deliver diffraction limited light to the focal plane instruments

<sup>3</sup>see ATST site survey at [atst.nso.edu/site](http://atst.nso.edu/site)

tion limited correction of images required for determining the magnetic field. Visible light polarimetry awaits a larger 349 actuator deformable mirror, which is presently being programmed for use in Summer 2011.

#### A4.5. Fast Imaging Solar Spectrograph

To better understand the fine structure of the solar chromosphere, NST is equipped with a Fast Imaging Solar Spectrograph (FISS, ?). This is a field-scanning slit spectrograph with high spectral resolving power ( $1.4 \times 10^5$ ) and fast scanning speed (10 seconds) to sufficiently cover a large field of view of  $40'' \times 60''$ . It has been developed for the NST by Korean Astronomy and Space Science Institute (KASI) and Seoul National University. The observable spectral lines range from visible to near infrared ( $0.38 \mu\text{m} - 0.92 \mu\text{m}$ ). The major spectral lines of interest for studying chromospheric dynamics are  $H\alpha$ , Ca II H and K and Ca II 8542Å. Two different spectral lines can be recorded simultaneously using two identical CCD cameras. This feature enables one to distinguish between the thermal component and the non-thermal turbulence, so that a precise determination of temperature will become possible.

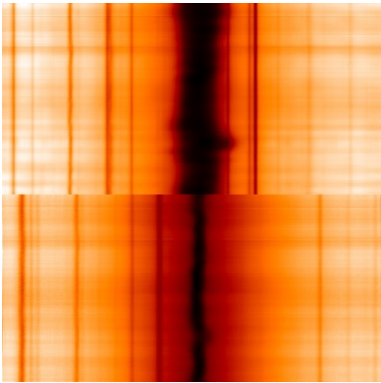


Fig. 6.— FISS spectra taken near the  $H\alpha$  (upper row, broad dark vertical feature is the  $H\alpha$  line) and Ca II lines (bottom panel). The high of the slit is  $40''$  and the spectral range covered by these images is about  $10\text{\AA}$ . At the lower part of the slit both lines in the spectra show significant line shift (a little bump on the right side of the  $H\alpha$  line. This “bump” is caused by strong down-flows of solar plasma. At the same time, one can also identify other “bumps”, on the left (blue) side of the spectral lines indicating plasma upflows.

## B. Results from Prior NASA Support

Here we highlight major findings relevant to the proposed research. The corresponding studies were supported by NASA GI and LWS grants, which expire in early in 2011.

- High-resolution chromospheric NST images revealed for the first time tiny jet-like structures originating in the dark lanes that surround the ubiquitous granules that characterize the solar surface. The tiny jets apparently have sufficient energy to resolve the mystery of why the overlying chromosphere is hotter than the photosphere.

*Publication: "Highest Resolution Observations of the Quietest Sun" by Goode et al. 2010, ApJL, 714, L31*

- We find that the BPs detected in NST images are co-spatial with those visible in Hinode/SOT G-band images. Extended filigree features are clearly fragmented into separate BPs in NST images. The distribution function of BP sizes extends to the diffraction limit of NST (77 km) without saturation and corresponds to a log-normal distribution. The lifetime distribution function follows a log-normal approximation for all BPs with lifetime exceeding 100 s. A majority of BPs are transient events reflecting the strong dynamics of the quiet sun: 98.6% of BPs live less than 120 s. The size and maximum intensity of BPs were found to be proportional to their life times.

*Publication: "Statistical Distribution of Size and Lifetime of Bright Points Observed with the NST" by Abramenko et al. ApJL, submitted*

- Based on New Solar Telescope  $H\alpha$  data and Hinode photospheric line-of-sight magnetograms and Ca II H images we report that i) even very small dipoles (elements separated by about  $0''.5$  or less) may reach the chromosphere and trigger non-negligible chromospheric activity; ii) bright points seen in off-band  $H\alpha$  images are very well-correlated with the Ca II H bright points. We also argue that the apparent collision and disappearance of two opposite polarity elements may not necessarily indicate their cancellation.

*Publication: "Chromospheric signatures of small-scale flux emergence as observed with NST and Hinode instruments" by Yurchyshyn et al. 2010, Astrophys. J., 722, 1970*

- Utilizing high-resolution NST and Hinode data, we demonstrated for the first time that in a quiet-sun area, photospheric plasma motions and magnetic fields are in equipartition over a wide dynamical range. If there is a fast turbulent dynamo in the quiet-sun photosphere, it could only exist on scales much smaller than 0.5 Mm.

*Publication: "Highest Resolution Observations of the Quietest Sun" by Goode et al. 2010, ApJL, 714, L31*



- Parameters of magnetic flux distribution inside coronal holes were analyzed. Hinode data show that at scales smaller than 2 Mm, the filling factor decreases rapidly, which implies a multifractal structure and highly intermittent, burst-like energy release regime.

*Publication: "Parameters of the Magnetic Flux inside Coronal Holes" by Abramenko et al. 2009, Solar Phys., 260, 43*

### C. Research Plan

Jets and the associated chromospheric dynamics may play an important role in coronal heating. Thus, ? and ? argue that ubiquitous coronal upflows observed in the lower atmosphere may be responsible for transfer of mass from the dense chromosphere into the corona and thus may be a key part of coronal heating and solar wind flows. Data further indicate that these upflows may have a chromospheric counterpart, so called rapid blue-shifted events (RBEs) associated with the network fields (??).

Observations of active regions offered some explanations for upflows observed in UV such as coronal reconnection (???), emerging flux (?) as well as intermittency at the edges of active regions (?), and active region expansion (?).

However, in quiet Sun areas and in coronal holes situation is less understood, mainly because of limited spatial resolution. Difficulties also arise from the fact that the chromosphere appears to be a very complex layer, and the complexity mainly comes from the temperature and density distribution.

**The main question is how the flows are driven?** Are they driven by mechanisms similar to those operating in active regions?

The origin of chromospheric upflows is not understood and the connection between smallest scale chromospheric activity and photospheric dynamics is not well explored. Here we propose to address the statistical properties and dynamics of photospheric BPs, which are co-spatial with strong magnetic fields (??). The bright unresolved clumps of BPs that comprise the magnetic network seem to be at origin of chromospheric upflows that quite possibly continue into the corona. BBSO's NST instrumentation can now resolve these bright clusters into individual bright points (Figs. ??), thus enabling us to link their evolution and

dynamics to the chromospheric activity.

### C1. Chromospheric Dynamics in Coronal Holes and Quiet Sun

Observations in the far blue wing of the  $H\alpha$  spectral line combine advantages of broadband and narrowband filters. Fig. ?? is an example of speckle reconstructed NST data obtained with a narrowband ( $0.25\text{\AA}$ )  $H\alpha$  Lyot filter shifted by  $1.0\text{\AA}$  toward the blue side of the spectra (see movie at <http://www.bbsso.njit.edu/2010LWS>). These blue shifted images make most apparent upward directed flows that have velocities up to 60 km/sec (dark features in the image), which are seen there against the background of photospheric granulation with inclusions of single BPs as well as clusters of BPs. Some of these bright features probably result from heating, however majority of them are magnetic BPs, i.e., those seen in G-band and TiO images.

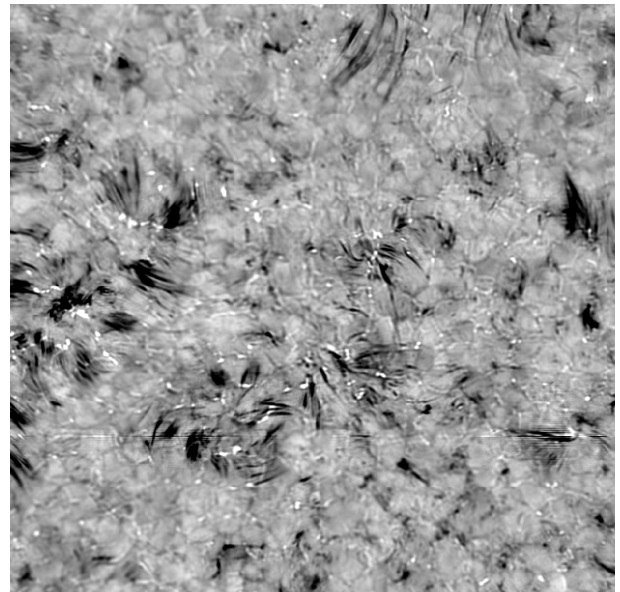


Fig. 7.— NST  $H\alpha$ - $1.0\text{\AA}$  image acquired on June 28, 2010. The dark features are upward directed flows that have velocities up to 60 km/sec seen against the background of photospheric granulation with inclusion of BPs. The corresponding movie reveals significant dynamics associated with these rosette like structures caused by clusters of BPs (<http://www.bbsso.njit.edu/2010LWS>).

There are several types of dark dynamic features apparent in that image. Most noticeable are the dark streaks that form rosette-like structures. They appear and fade without showing any significant bulk motion

along the arc. According to ?, they can be identified as rapid blue-shift events (RBEs) or straws, and are thought to be disk counterparts of the type II spicules.

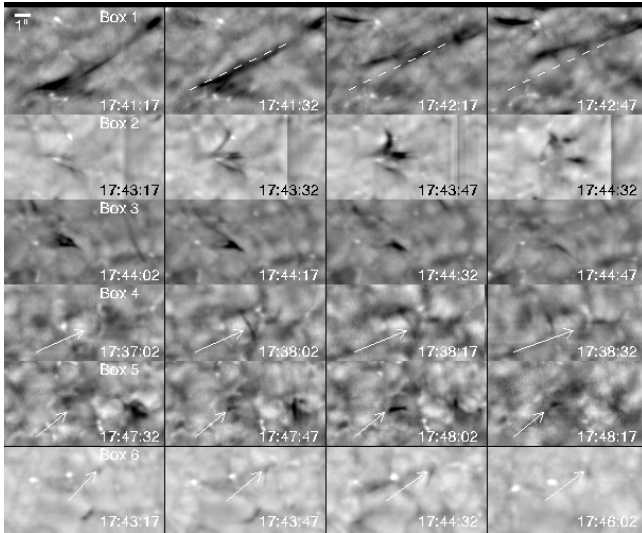


Fig. 8.— Time evolution of selected events observed on August 27, 2009 without adaptive optics. The top row shows a possible interchange reconnection event when a dark elongated structure moved sideways (the dashed line marks the initial location of the feature as determined from the 17:41:17UT frame) with a velocity of about 20km/s. Second row shows dynamics associated with a bright point. Row 3 shows an inverted “Y” event, consistent with reconnection between a closed loops and a large scale field. Rows 4 and 5 show tiny jets discovered by NST that arcs over a granule seeming to bisect it, while the row 6 is an example of an event emerging from a dark lane (<http://www.bbo.njit.edu/2010LWS>).

The NST sees previously unknown, even finer chromospheric features in the  $H\alpha$ -1.3Å data (Fig. ??, 3 bottom rows). They appear to be very small, dark, and short lived jet-like upflows (Doppler shifted to the blue) arising from the dark inter-granular lanes. Their presence in these far blue shifted images does indicate strong plasma upflows, although it is not clear at this moment how strong they appear in the red-shifted images, which would reveal plasma downflows.

Their origin seems neither to be unequivocally tied to strong magnetic field concentrations accompanied by bright points nor predominantly associated with the vertex formed by three (or more) granules. Rather, they most frequently stem from an intergranular lane separating two granules, which are known to host strong magnetic fields too, even without bright points

being apparent there (??). These intergranular events were not resolved in any earlier high resolution off-band  $H\alpha$  images (e.g., Fig. 2c in ?; Fig. 7 in ?; Fig. 2 in ?). The projection of these jets-like features onto the image plane may reach of typical length of 1Mm, while maintaining their width at 0.2Mm during a typical lifetime of 30-60s (some as long as 4min).

We would like to learn more about the origin of these tiny jet-like structures and other dynamics events. How are RBEs related to the clusters of bright points? Do they occur in relation to a single bright point? If so, what are the conditions of its occurrence? Are the chromospheric dynamics mostly limited to the network fields? How are BPs distributed in CHs and in quiet sun areas?

All those questions will be properly addressed in the proposed study. We believe that they are timely not only because there has always been an increasing interest to chromospheric and coronal heating, but also because the existing instrumentation allows us to address them.

NST provides multi-wavelength data with higher spatial and temporal resolution than the aforementioned instruments, which enables us to reveal more details on small-scale photospheric dynamics and thus significantly contribute to this topic. For example, TiO and G-band data will be compared with the co-spatial  $H\alpha$  spectral data suitable for detection of various chromospheric dynamics such as jets and spicules (see also next Section). Co-temporal high resolution IRIM magnetograms will be valuable here as well. These data will enable us to find out whether RBEs only occur where and when a small-scale fields of opposite polarity are pushed against a cluster of network fields. It appears to be a possibility, since the RBEs tend to crown the extended clusters of bright points, which gives an impression that they originate at the edge of the cluster and the photosphere is full of turbulent horizontal magnetic field (?) and granular-scale flux emergence (???)

## C2. Statistical and Case Studies of Bright Points

*Motivation.* Bright points (BPs) observed in the solar photosphere in FeI 6173 Å (?) and G-band images (??) are shown to be co-spatial, and co-temporal with magnetic elements. The relationship between BPs and

the magnetic field seems to be so solid that the former are frequently addressed as magnetic bright points (e.g., ??). The mechanism for the formation of BPs is thought to be a convective collapse of a magnetic flux tube (??) implying strong downflows and evacuation of the flux tube allowing us to look deeper and see hotter side of a granule(s).

Enhanced interest to BPs is partially due to the fact that they are very reliable tracers of the transverse motion of foot points of vertical magnetic fields. These motions are thought to be the energy source for chromospheric and coronal heating. The energy stored in the magnetic fields can be converted into heat either via dissipation of waves or magnetic reconnection of intertwined flux tubes (e.g., reviews by ??? and references therein).

These and other considerations stimulated numerous studies of horizontal motions and the results were used to improve our understanding of wave generation (e.g., ?) and reconnection (?) and references herein.

Existing data on BPs are either of inferior spatial and temporal resolution and/or cover short time intervals, thus precluding detailed studies of BP displacement. For example, according to our recent study based on 10s cadence data NST data (?), the overwhelming majority of detected BPs were small and had lifetime shorter than 2 min (Fig. ?? and ??), which

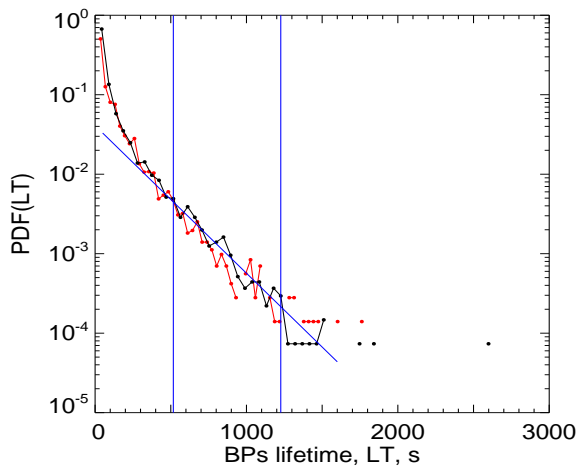


Fig. 9.— Lifetime distribution of BPs as determined using 85 DN (black) and 120 DN (red) thresholds. The thick blue line is the exponential fit to the data points between the vertical blue lines.

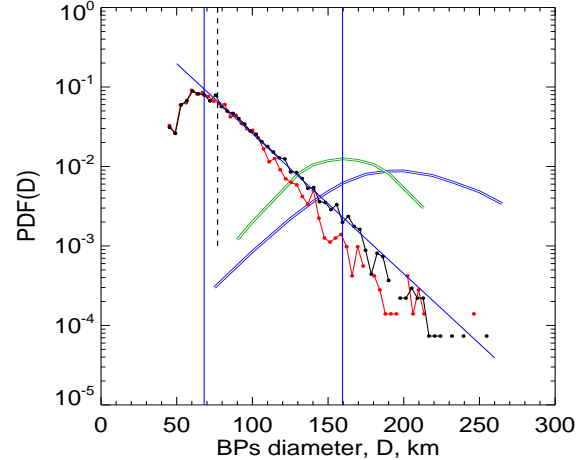


Fig. 10.— Distribution of BP diameter as determined using 85 DN (black) and 120 DN (red) thresholds. The blue line is the exponential fit to the data points between the vertical lines. The dashed line segment indicates the NST's Rayleigh diffraction limit for TiO data. The double curves show the BP size distribution determined from Hinode G-band data by ?: the blue (green) double line represents the PDF for  $0''.109$  ( $0''.054$ ) pixel data. As it follows from the plot, there are many short lived and small BPs, which can account for the variety and intensity of small scale chromospheric dynamics.

implies that 30 sec cadence data is not really adequate for resolving their behavior (see the description of BP tracking further in the text). In low cadence data, short lived BPs appear in only 1-2 images and such events were previously removed from studies as unreliable. Instead, the focus was on large and long living events. For example, measuring motions of BPs, ? proposed that strong chromospheric flows could be the result of horizontal displacement of BPs.

Figure ?? shows distribution of the BP diameter as measured from NST/TiO images using two different thresholds. The BP diameters distribution displays a nearly linear behavior down to the NST's diffraction limit of 77km. The saturation and the turnover of the PDF at scales smaller than 77km (to the left from the dashed vertical line) might be caused either by the fact that NST does not completely resolve elements smaller than 77km, and/or that elements much smaller than that do not exist. For comparison, in the same panel we show BP size distribution as derived from Hinode/SOT G-band images by ?. In spite of a drastic difference, physically, NST and Hinode

PDFs are consistent. The Hinode PDFs also saturate at scales corresponding to the diffraction limit of the instrument, which is 157km for SOT observations in the G-band.

Figures ?? and ?? convincingly illustrate how much information we are missing when observing with insufficient spatial and temporal resolution. The most important point here is that the high rate of appearance of these small and short living BPs significantly increase dynamics (flux emergence, collapse into BPs, field restructuring, and magnetic flux recycling) of unipolar network areas. These unipolar fields make it difficult to invoke reconnection between the emerging and pre-existing flux as driver for the RBEs. However, the fact that the network field is more dynamic than it appears may allow to apply the component reconnection approach. The magnetic field is fragmented into flux concentrations with well defined interfaces between them known as current sheets. Random motions of BPs, as well as often appearance/disappearance of new flux concentrations, will change the spatial distribution of the current sheets thus leading to component reconnection and to release of energy accompanied by burst like upflows that deposit energy and material in the chromosphere and corona.

**To really understand the coupling between the chromosphere and photosphere and how the solar corona is heated, it is necessary to understand the dynamics of the photospheric magnetic flux. NST instruments are uniquely suitable for this task. NST allows us to routinely observe photospheric BPs with unparalleled clarity (Figs. ??, ??, ??). High spatial resolution, together with possibility to perform long observing runs (up to 3 hours) under stable seeing and with high time cadence (10 s) is ideally suited to address the problem of BP evolution and their association with chromospheric activity. Thus our work is an essential component to the effort to connect the chromosphere to the corona.**

*Method.* To detect and track BPs, we developed a BP tracking routine (Abramenko et al. 2010), which is based on the facts that: i) BPs are of small size; ii) they have enhanced intensity and iii) strong intensity gradient at the edges of BPs (?). A mask is calculated based on thresholding a difference image obtained by subtracting an averaged image from the original one. The threshold may vary: high threshold allows us to

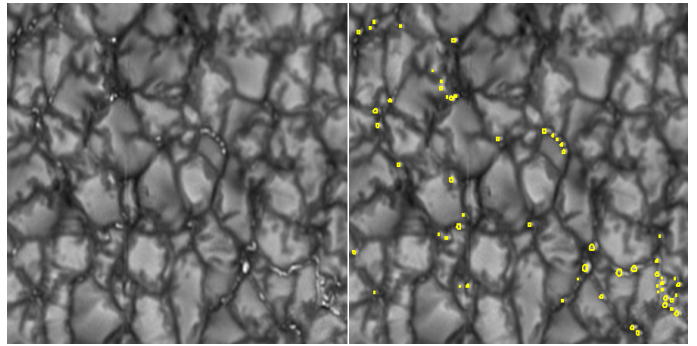


Fig. 11.— In both panels the background is the same and shows an NST TiO image observed on Aug 3, 2010. The yellow contours in the right panel encompass the bright points detected with the described routine. For each detected BP we can determine a variety of parameters including area, peak intensity, and diameter as well as follow their time evolution (<http://www.bbso.njit.edu/2010LWS>).

only detect apexes of the brightest BPs, while lowering threshold leads to detecting progressively weaker elements. An example of BPs detection with high threshold is shown in Fig. ?? and ??. As mentioned it earlier, TiO data are very well suited for addressing temporal evolution of BP (appearance/disappearance) and their motions.

For each BP in an image, we determine a variety of parameters including area, peak intensity, BP equivalent diameter ( $d$ , diameter of a circle whose area is equal to the BP's area) as well as coordinates ( $x_c, y_c$ ) of the center of the equivalent circle.

We then track detected BPs from one image to another. One important requirement should be satisfied during the tracking: the BP displacement from one image to another should not exceed the equivalent radius. The advantage of this approach is that it allows us to reliably trace sub-sonic displacements of BPs of radius larger than 3 pixels. The shortcoming is that we are not able to track small BPs with large displacements (velocities  $> 4-5 \text{ km s}^{-1}$ ). It was undesirable to adopt a broader search range since BPs are frequently located very close to each other and tracking of the same BP is not guaranteed in that case. We also assume that a BP ceases to exist when it either does not show up in four consecutive images (time interval of 40 s) or it merges with another BP.

Figure ?? show the result of BP tracking. There, a granulation image is over-plotted with tracks of all long lived BPs ( $> 3\text{min}$ ) detected in the data set. Track-

ing BPs for nearly 2 hours reveals that BPs tend to repeatedly appear at nearly the same location, which may indicate both strong advection toward the convection cell boundary and new flux emergence.

Figure ?? is an example of a trajectory of a long lived BP. Several interesting things can be noted about this track. First, it shows a wave-like behavior with a period of about 15min (between  $y = 365$  and  $y = 410$ ). These swaying motions are likely due to granules pushing the BP as they develop. Judging from the track, this BP probably spent the last moments of its life at a stagnation point (vertex of intergranular lanes) being rapidly buffeted left to right around a fixed point. What is the source of these motions? What is the chromospheric activity associated with this BP, if any? Are the periods of rapid BP motions or “jumps” seen between  $y = 380$  and  $y = 390$ , associated with detectable chromospheric activity? What happened at the stagnation point? How many BPs display any vortex like

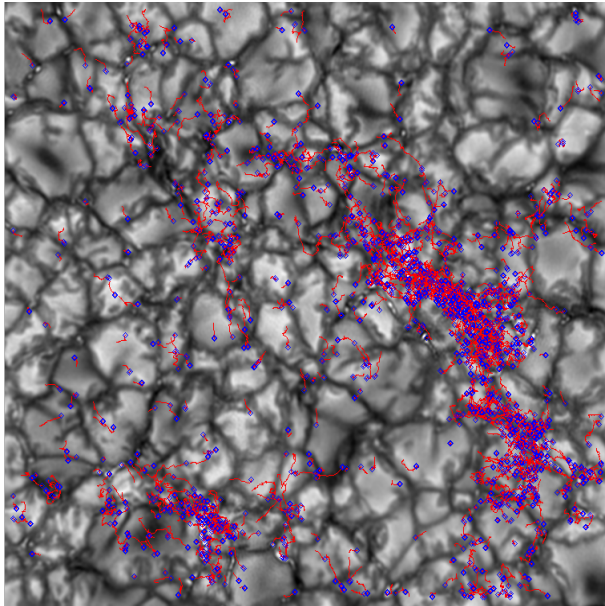


Fig. 12.— *TiO* image with over-plotted trajectories of only long lived BPs detected in the data set. The blue diamonds mark the beginning of a track. The purpose of this figure is to illustrate the general dynamics of BPs, which is not obvious from visual inspection of images and movies. Tracking BPs for nearly 2 hours reveals that BPs are highly dynamics entities. They are relentlessly and repeatedly appearing at nearly the same location, which may indicate either strong advection toward the convection cell boundary or new flux emergence or reappearing of the same BPs or all of the above. (<http://www.bbo.njit.edu/2010LWS>).

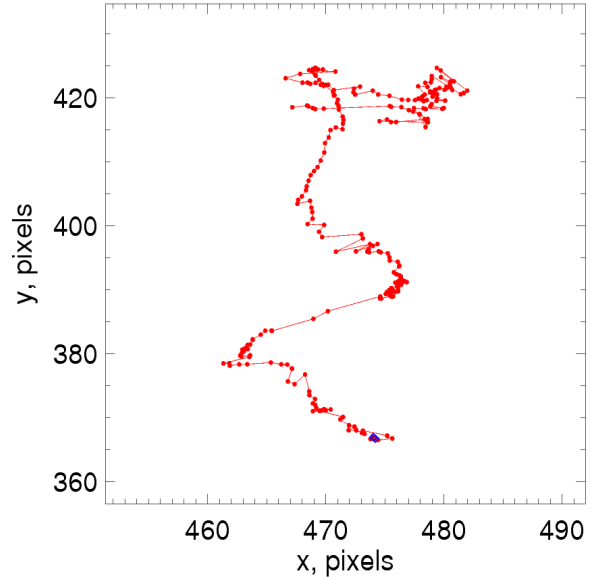


Fig. 13.— *To illustrate potential of NST data and the tracking routine, we show a track made by a long lived BP (track starts at the bottom). Each point represents a moment of time when the BP was detected in an image. The BP showed a wave-like motions with a period of about 15 min (between  $y = 365$  and  $y = 410$ ), while the last moments of its existence the BP spent at a stagnation point (vertex of intergranular lanes) being rapidly buffeted left to right around a fixed point. What is the source of these motions and what was the associated chromospheric activity? These and other questions can be answered in the course of a statistical study based on high cadence and high resolution NST data.*

motions (??) that could generate upflows (?). What was associated chromospheric activity there? What is the energy spectrum of these motions? These and other questions can only be answered in the course of a statistical study based on high cadence and high resolution NST data. In this proposed research we will do the following:

- Track BPs in various data sets, generate BP tracks and calculate various parameters of BP evolution. We will analyze these tracks and search for sudden accelerations, vortex motions or intersections with other tracks. We will then search for chromospheric activity that could have been caused by all these peculiar motions. The tracks will be used to build auto-correlation curves, for example, which describe temporal variations of BP motions and could be utilized to derive a velocity spectra needed to improve models of coronal heating via MHD waves (e.g., ?).
- Using tracking results, we will analyze rate of BP

appearance, lifetime, etc. and relate the results to the associated chromospheric activity.

- Particular attention will be paid to instances when a jump of a BP is observed. These rapid displacement of magnetic footpoints are thought to be effective in generating transverse MHD waves that may contribute to chromospheric and coronal heating (??). First question we would like to answer is what is the driving force behind those jumps? Is it expanding/collapsing granules that locally push BPs? Or, may be these fast BPs are advected to the boundaries of meso- and super granular cells by large-scale flows? Is reconnection involved in this process (e.g., interchange reconnection)?

- Finally, LCT flow maps will complement the tracking results and help us to reveal general pattern of the flows on variety of scales. First results from application of the LCT method to NST data were presented in ?. In particular, the spatial and temporal resolution of NST was sufficient to show a case when converging motions seemed to cause intensity enhancement in a BP. How typical are these events? More importantly, what is their signature in the chromosphere? The disadvantage of this technique is that it is insensitive to stationary flows and thus cannot detect plasma motion, say, from the center of the granule to its edge. However, this disadvantage can be overcome when flows are fragmented and/or there are temperature variations along the flow. Indeed, TiO movies show that this is the case (<http://www.bbso.njit.edu/2010LWS>). Granules in the NST images do not appear as a uniform entity with the intensity gradually decreasing from the center to the edges (a dome like structure). They rather look like a “dented” surface consisting of constantly flowing brighter and dimmer areas. NST data sampling is sufficient to resolve these flows with the LCT and thus address questions related to their fine scale organization.

### C3. Fine Structure of Solar Magnetic fields

It has been suggested that magnetic reconnection may play a significant role in solar wind acceleration and coronal heating (e.g., ???????). However, for this mechanism to work, magnetic complexity should be present at many spatial scales, i.e., magnetic fields on the solar surface should not only display mixed polarity but also have strong and abrupt variations in

magnitude.

Interestingly, Hinode magnetic field data revealed that on spatial scales smaller than 2Mm ( 3" ), the filling factor in a CH sharply decreases (?), which is expected and happens in highly complex magnetic field structures that exhibit strongly intermittent, burst-like energy release behavior. This finding indicates that in CHs energy release occurs at scales below 2Mm, where mixed polarity fields dominate. This conclusion agrees well with the recent discovery (?) that the fast solar wind originates in small-scale coronal magnetic funnels rooted at the edges of the magnetic network and surrounded by numerous small-scale magnetic fields continuously brought up to the surface by solar convection (e.g., ?) .

Figure ?? plots flatness functions (reciprocal of the filling factor) of the line-of-sight fields measured in a typical active region and quiet-sun area. Again, while the flatness function is flat (dashed line) for a non-intermittent, non-flaring structure, it becomes steeper with decreasing spatial scales for intermittent fields. The steeper the function, the more complex fields are. Similar to active region fields, these complex small scale fields in QS and CHs are equally capable of producing a variety of active events (but on a smaller scale, of course).

Since the small-scale fields seem to be at the root of chromospheric upflows (which, in turn, are apparently related to the solar wind acceleration and coronal heating) their evolution and statistical properties appear to be relevant to the formation of chromospheric jets. While in the previous Section the emphasis was on tracking BPs, which are proxy for the magnetic field, here **we propose to significantly expand on our initial efforts and explore the statistical properties of these fields. The NST IRIM instrument enables us to make significant progress in this direction by providing high quality magnetograms (0" .05/pixel and 0" .2 diffraction limit).**

What is the magnetic field distribution in the QS and CHs? Are the magnetic field parameters the same and how do they change depending on the type of structures (network, inter network, coronal holes)? Are magnetic field dynamics measured in predominantly network/plage areas the same as in inter-network zones? We know that the chromospheric activity there is different.

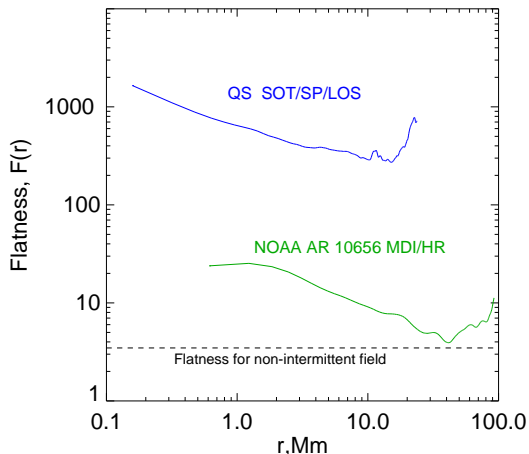


Fig. 14.— Flatness functions (reciprocal of the filling factor) of line-of-sight fields measured in a typical active region (SOHO/MDI high resolution data, pixel size of  $0''.6$ ) and for a typical quiet-sun area observed with Hinode/SOT/SP with a pixel size of 0.16 arcsec. Flatness function is flat (dashed line) for a non-intermittent, non-flaring structure and it becomes steeper with decreasing spatial scales for intermittent fields capable of burst-like energy release. The steeper the function, the more complex the fields are. The plot emphasizes the idea that complex small-scale fields in QS and CHs are equally capable of producing a variety of active events.

**Another very important use of the results of this research is to constrain various models of solar granulation.** For example, simulations show that granular flows tend to concentrate magnetic fields into uniform continuous “sheets”, while observations show that that these sheets are in fact conglomerates of many BPs. This disagreement is important. It is apparent now that relative displacements of BPs within a cluster (which corresponds to a “sheet” in simulations) are critical for releasing energy and producing flows. Simulations seem to be unable to resolve the magnetic sheets, thus they are missing a bulk of the motions vital to chromospheric and coronal heating. **We will explore whether simulated and observed small scale fields have similar characteristics. We are currently applying our codes to several simulated data sets kindly provided to us by R. Stein (see modeling results in ?) The LWS focus science team could greatly expand on this effort. This is another topic on which BBSO team could collaborate within the LWS group.**

## D. Project Management

### D1. Research Plan and Schedule

*Year 1. (starts in Spring of 2011)* We will continue to collect NST data and organize NST and Hinode joint observational campaigns. As data flows in we will identify the best quality NST sets and will complete these sets w/ data from other instruments. To each data set we will apply the existing codes to follow the evolution of individual BPs and study their motions. Also, flow maps will be constructed. At this moment we will have (at least) one complete data set and preliminary results sufficient to be presented at first team meeting. We expect that the first meeting will draft team’s long term research plan and will set up a stage for many collaborations between team members (such as organizing joint obs. campaigns, data analysis and interpretation).

We will continue to analyze the available data and incorporate ideas and suggestions worked out at the team meeting. We also plan to develop additional codes to track flux emergence as well as rapid and intense changes in the intensity fields. By the end of the year we expect to have publishable results. Prepare first year progress report.

*Year 2. (starts in Spring of 2012)* During the 2012 observational season, we will resume NST observations, some of them will be joint campaigns with Hinode and SDO. To increase efficiency of the joint campaigns we will observe whenever possible in the “following Hinode” mode, when the NST is routinely pointed at the current Hinode target (Hinode pointing info is available online). Fortunately, SDO instruments take high resolution high time cadence full disk images around the clock, so no special observation coordination is required. Alongside observations we will perform data processing and compiling data an extensive data sets that would include both ground and space based measurements. This activity assumes involvement of some LWS team members (we hope that there will be expert in, for example, Hinode/EIS, Hinode/SP and SDO/HMI data processing and interpretation). Prepare second year progress report.

*Year 3. (starts in Spring of 2013)* Continue to data acquisition with NST and data processing. Continue team collaborations. Submit papers for publication in *Astrophysical Journal*. Prepare final progress report as

well as final team's report.

## **D2. Management Plan**

The people involved in the proposed research and their skills were presented earlier in Section A.3. Here is detailed description of their responsibilities.

- NST observation and campaigns - V. Yurchyshyn, V. Abramenko, W. Cao
- BP dynamics and fine structure of magnetic fields in CH and quiet Sun - V. Abramenko, W. Cao
- chromospheric dynamics in in CH and quiet Sun - V. Yurchyshyn

V. Yurchyshyn (PI) and V. Abramenko (Co-I) are research staff and no permanent funding is provided for them by New Jersey Inst. of Technology. The proposal seeks funding for 4 months of salary (per year) for the PI and 6 months (50%) of salary for the Co-I. The remaining salary (50% of V. Abramenko and 60% of PI's) salary will be paid from our current NSF and NASA grants. Prof. W. Cao is a non-funded Co-PI: his salary is paid by New Jersey Inst. of Technology.