

Title of Investigation: Studies of the Solar Atmosphere Using Coordinated Observations with the New Solar Telescope and NASA Solar Physics Missions

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Proposal Summary

In the last two years since the start of our current SR&T grant, Big Bear Solar Observatory (BBSO) has remained highly productive – both scientifically and in the development of requisite instrumentation. This productivity includes bringing online our 1.6 m clear aperture off-axis solar telescope with light corrected by adaptive optics, while publishing over forty papers.

We have also integrated our near-infrared (NIR) imaging vector magnetograph, adaptive optics, fast imaging spectrograph, and visible light real-time image reconstruction system to the NST, as well we are upgrading the adaptive optics and bringing online our visible light imaging magnetograph. These all will be available from the outset of funding this proposal to provide diffraction limited data in visible and NIR light. All of these NST efforts are well-timed and focussed to provide unique support for Hinode, SDO, STEREO and RHESSI.

Our proposed research will focus on the following (STRAWMEN SKELETAL TARGETS):

1. High-cadence and high-resolution observations of flow fields and magnetic fields in both the quiet and active Sun to elucidate the origin and evolution of the small-scale dynamics that underly the spectacular events of the chromosphere and transition regions. We will use NST flow field data with $0''.07$ and $0''.20$ spatial resolution in the visible and NIR, respectively, and vector magnetograms with about twice the spatial resolution of the photometric observations. The temporal cadence in the diffraction limit will be about 5 s and 30 s for photometry and polarimetry, respectively. Faster cadences are possible with some sacrifice. NST visible light and NIR data will enrich Hinode and SDO research.

2. High resolution, sub-second measurements of flow fields to probe the triggering mechanisms of prominences, flares and CMEs. The NST will be complementary to Hinode and SDO in these studies.

3. NEED (???) TO DEVELOP ROLE OF NST in providing the lower boundary conditions in un-

derstanding and modeling of dynamical events, likes prominence eruptions, flares and CMEs as detected by satellite data.

NST data will be available online and on VSO to complement and supplement NASA satellite data. NAME ONE EXAMLE (???)

The proposed research is clearly related to NASA's strategic goal 3B: to understand the Sun and its effects on Earth.

A. Results from Prior NASA-SR&T Support (Jan. 2009 to Dec. 2010)

On January 1, 2009, our current three-year SR&T grant started. This grant is one of two backbone grants supporting Big Bear Solar Observatory (BBSO). After several years of effort, in January 2009, BBSO attained first light with its off-axis, 1.6 m clear aperture New Solar Telescope (NST). First diffraction limited observations with the NST came in the Summer of 2009, while the first observations corrected by adaptive optics (AO) came in the Summer of 2010 along with the first vector magnetograms with the NST. We show in Fig. 1 diffraction limited images of the photosphere (in TiO at 705.7 nm) and chromosphere (in H α at 656.3 nm). The upper image has been called the most precise image of the Sun's surface ever taken (<http://www.cieletespace.fr/node/5752>) and was chosen by the editors of National Geographic as one of the top ten space images of 2010 (<http://news.nationalgeographic.com/news/2010/11/photogalleries/101130-best-space-pictures-2010/>).

The NST will significantly broaden and deepen BBSO's tradition of providing data from campaigns in coordination with those of NASA satellites, like SDO, Hinode, RHESSI and STEREO. That is, the NST will provide unique high temporal and spatial resolution data to complement NASA's efforts to understand the fundamental nature of the dynamics of solar magnetism and its evolution. The NST's ability to precisely observe the photosphere and chromosphere dovetails well with the overlapping satellite observations that tend to be concentrated higher in the solar atmosphere. Our capability of running sustained campaigns has been at the core of our ability to provide unique, complementary and supplementary data in support of the NASA community's efforts to understand our star and its terrestrial effects (WENDA DOESN'T LIKE???). Observing campaigns are essential to determine the origin of "space weather", which arises from solar magnetic storms and can have deleterious effects on satellites, as well as the terrestrial power grid and telecommunications.

Key among what we propose are: (1) A; (2) B; (3)C; and (D) Further, we will make NST data online in a user-friendly way as well as providing these to VSO. (SEE ABSTRACT EVEN THO IT IS WEAK)

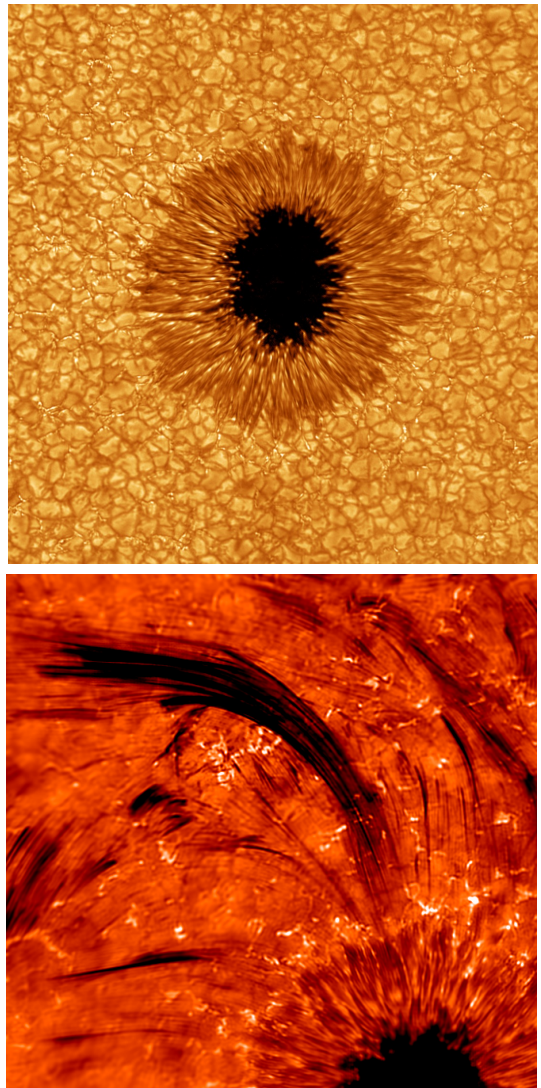


Figure 1: Top: A small sunspot observed on 2 July 2010. Bottom: H α image of the same sunspot revealing the dynamical layer overlying the surface region shown in the full sunspot image. Most apparent are the long dark streaks, so-called "jets" arising from the bright magnetic regions on the edge of the penumbra. Both images used adaptive optics enabling real-time correction for atmospheric distortion.

The NST is the pathfinder for the Advanced Technology Solar Telescope (ATST) that will be built in Hawaii over the next decade. Both the NST and the 4 m ATST have off-axis designs. The NST will dominate U.S. ground-based observations at least until the latter part of the new decade. After the ATST is online, the NST will still have an essential role because the NST will be the large aperture solar telescope in the U.S. (SHOULD WE MENTION GREGOR???) working in sustained campaigns. We continue to make systematic, fundamental changes in the

observatory's instrumentation to ensure a unique and significant scientific role for BBSO. The advances in instrumentation were critical for improving the quality of our observations. We have, and will continue to devote considerable effort to instrument development with the NST already being well into its commissioning phase. The resulting improvements in data quality helped our research group to advance the understanding of the Sun, while being very productive, as evidenced by over 40 publications in the two years since Jan. 2009.

NJIT continues to strongly support our efforts, and would match this grant with \$300 K for new equipment for the observatory. It is also fully funding two lead staff positions for the NST and beyond - the NST Project Director (Roy Coulter) and the Optical Engineer (Nicolas Gorceix).

BBSO highly prizes its special role in the education of the next generation of scientists who build instruments. In recent years, three of our post-docs have advanced to tenure-track faculty positions in the U.S.. Wenda Cao is now an assistant professor at NJIT. Jiong Qiu is an assistant professor at Montana State University. Deqing Ren is an assistant professor at California State University, Northridge. Two of the three are scientists who build instruments. Over the last decade, eight other former BBSO/NJIT post-docs have earned professorships in their home countries. These include Jongchul Chae (Korea), Carsten Denker (Germany), Haisheng Ji (China) and Peter Gallagher (Ireland). Prof. Chae was on sabbatical in Big Bear during the 2009-10 academic year leading the effort to bring on line the NST's fast imaging spectrograph, which was built in Korea with Korean funds. Chae and Denker are scientists who build instruments. Since 2000, NJIT has graduated more than 20 PhD students and most used BBSO data, and eight are working in solar physics research.

Presently, BBSO has seven scientists in residence including three women. We judiciously mentor our junior people at BBSO. We do this by carefully integrating each into the research and/or instrumentation teams to broaden experience while maximizing the intellectual productivity of each. We have a video conferencing center on site in Big Bear, so we can have joint seminars and enable classroom teaching from NJIT to BBSO, and vice versa.

BBSO has an unpaid, outside Advisory Board that

meets bi-annually to critique our efforts. The Board's report is made to the upper management of NJIT and passed on to BBSO management. The current members of the board are Len Fisk (University of Michigan, Chair), Oskar van der Lühe (Kiepenheuer Institut, Germany), Ken Libbrecht (Caltech), and Jeff Kuhn (University of Hawaii). NJIT respects their advice and has used it to improve the observatory.

Since NJIT began operating BBSO, its telescope time and data have been open to the community. Many scientists have had observing time. Students from around the world have used BBSO data as a central part of the thesis work of each. Data requests come to BBSO on a daily basis from around the world. The NST will generate far more data than the old telescope and making the NST data available to the solar community in a useful way presents a more sophisticated problem that is discussed in **B.4**. Some NST data are already available on our website (<http://www.bbsol.njit.edu>). We have implemented an internal fiber optic link and a RAID array for our FTP archive. For users of our telescopes and data, we only ask that they acknowledge BBSO in their resulting publications.

BBSO achievements in instrumentation will be included in the on-going instrumentation section, while for the remainder of this section, we focus on the highlights of some of our scientific achievements under current SR&T support. Our publications, in the form of BBSO Bluebooks, are also available on our website (see <http://solar.njit.edu/publication.htm>). (???CHECK THIS)

A.1 Quietest Sun Observations

Goode et al. (2010a) made diffraction limited, quiet Sun observations with the new 1.6 m aperture solar telescope in BBSO during the recent time of historic inactivity on the Sun, which revealed new insights into the small-scale dynamics of the Sun's photosphere. The telescope's unprecedented resolution enabled us to observe that the smallest scale photospheric magnetic field (so-called "bright points" (BPs)) seems to come in isolated, round points in the dark intergranular lanes, and many (more intense ones) have an unexpected longevity implying a deeper anchoring than predicted.

Goode et al. (2010a) also demonstrated for the first

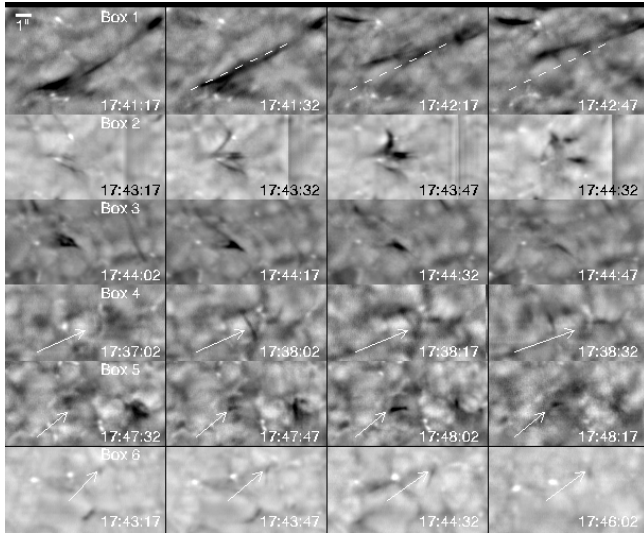


Figure 2: Time evolution of selected events observed on August 27, 2009 without adaptive optics. The top row shows a possible interchange reconnection event when a dark elongated structure moved sideways (the dashed line marks the initial location of the feature as determined from the 17:41:17UT frame) 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.bbso.njit.edu/2010LWSblack>).

time that the photospheric plasma motion and magnetic fields are in equipartition over a wide dynamic range, and both cascade energy to ever-smaller scales according to classical Kolmogorov turbulence theory. This result provides strong support for the important MHD assumption of an equipartition state in the photospheric magnetized plasma. Goode et al. (2010a) combined NST quiet Sun and Hinode data by expressing the plasma and magnetic field of the quiet Sun in terms of the Fourier transforms of their respective observed energy densities.

(SECTIONS A.2, A.3 AND A.4 ALSO PROPOSE WORK AND MAYBE THESE BELONG ON PART B???)

A.2 Chromospheric Dynamics in Coronal Holes and Quiet Sun

Goode et al. (2010a) discovered tiny jet-like features originating in the dark lanes and arcing across

a single granule. Observations in the far blue wing of the $H\alpha$ spectral line combine advantages of broadband and narrowband filters. Fig. 2 shows the arcing “jets”, and is an example of speckle reconstructed NST data obtained with a narrowband (0.25 \AA) $H\alpha$ Lyot filter shifted by 1.0 \AA toward the blue side of the spectra (see movie at <http://www.bbso.njit.edu/2010LWSblack>). These blue shifted images make most apparent upward directed flows that have velocities up to 60 km/sec (dark features in the image). In Fig. 2, one can see previously unknown, very fine scale chromospheric features in the $H\alpha -1.3\text{\AA}$ data (Fig. 2, three 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, and they do not appear to be strong 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 (Langangen₂₀₀₈; Ishikawa₂₀₀₈). These intergranular events were seen in $H\alpha$ images (e.g., Fig. 2c in counterparts; Fig. 7 in Langangen₂₀₀₈; Fig. 2 in Bergert₂₀₀₁). The projection of these like features onto the image plane may reach a typical length of $1M$ 60 s (some as long as 4 min).

We would like to learn more about the origin of these tiny jet-like structures and other dynamics events. How are Rapid Brightening Events (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 NST and NASA satellite instrumentation allows us to address them.

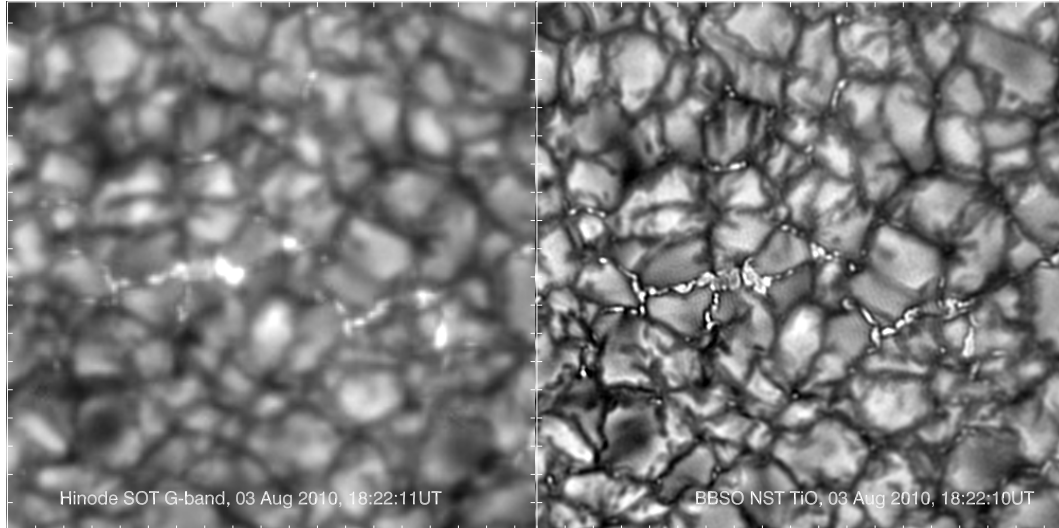


Figure 3: *NST* instruments are now actively collecting data. Here we show a $19'' \times 19''$ *Hinode/SOT* G-band (left) and *NST* TiO (right) image of the same area of the Sun acquired on Aug 3, 2010. Note the one-to-one correspondence between G-band and TiO bright points. The *NST* image clearly displays several tight clusters of resolved bright points (BPs) near the center of the field of view (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.

A.3 Chromospheric Signatures of Small-Scale Flux Emergence as Observed with *NST* and *Hinode* Instruments

With the ever increasing influx of high resolution images of the solar surface obtained at a multitude of wavelengths from the ground and space, various processes occurring on small spatial scales have become a greater focus of attention. Complex small-scale magnetic fields have been reported that appear to have enough stored to heat the chromosphere. While significant progress has been made in understanding small-scale phenomena, many specifics remain elusive. Yurchyshyn et al. (2010) performed a detailed study of a single event of disappearance of a magnetic dipole and associated chromospheric activity. Using *NST* $H\alpha$ data (the lower panel of Fig. 1 illustrates the quality of the *NST* $H\alpha$ data) and *Hinode* photospheric line-of-sight magnetograms and Ca II H images we reported that: 1) Even very small dipoles (elements separated by about $0''.5$ or less) may reach the chromosphere and trigger non-negligible chromospheric activity. 2) Careful consideration of the magnetic environment where the new flux is deposited sheds light on the details of magnetic flux removal from the solar surface. In detail, the apparent collision and disap-

pearance of two opposite polarity elements may not necessarily indicate their cancellation (i.e., reconnection, emergence of a “U” tube or submergence of Ω loops). In our case, the magnetic dipole disappeared by reconnecting with overlying large-scale inclined plage fields. 3) Bright points seen in off-band $H\alpha$ images are very well-correlated with the Ca II H bright points, which in turn are co-spatial with G-band bright points. We further speculated that, in general, $H\alpha$ bright points are expected to be co-spatial with photospheric BPs, however, a direct comparison is needed to refine their relationship. One can see in Fig. 3 that we can sharpen our study here with the addition of more *NST* data.

A.4 Statistical Distribution of Size and Lifetime of BPs Observed with the *NST*

The *NST* regularly produces many, several hour long sequences of diffraction limited images of the quality indicated in the right panel of Fig. 3. A typical movie may be viewed on the BBSO website (<http://www.bbso.njit.edu>), which shows an AO corrected, two-hour uninterrupted sequence of solar granulation obtained under excellent seeing conditions. In Abramenko et al. (2010), the AO corrected observa-

tions were performed using a broad-band TiO filter centered on the 705.7 nm spectral line with a time cadence of 10 s and a pixel size of $0''.0375$. Photospheric bright points (BPs) were detected and tracked. We found that the BPs detected in NST images were co-spatial with those visible in Hinode/SOT G-band images. In cases where Hinode/SOT detects one large BP, NST detects several separated BPs. 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 longest registered life time was 44 min. The size and maximum intensity of BPs were found to be proportional to their life times. Basically, there are evermore BPs on ever smaller scales and peak in their distribution reflects the resolution of the telescope, rather than a fundamental scale for BPs. This no apparent lower limit on their size and that they have a different character than generally ascribed to them (SAY MORE; REFERENCE TO SIMULATIONS).

A.5 Selected BBSO Publications from January 2009 to December 2010

The discussion above sketches some highlights of our scientific accomplishments over the past two years. Due to limited space, we list only selected publications (20 of 40) from the period of our present SR&T support. Please check the home page (<http://solar.njit.edu/preprints>) (IS IT PREPRINTS OR PUBLICATION OR PUBLICATIONS???) for a complete list with downloadable copies.

(HOW TO MAKE REFERENCES HAVE NO INDENT???)

Highest Resolution Observations of the Quietest Sun, 2010, P. R. Goode, V. Yurchyshyn, W. Cao, V. Abramenko, A. Andic, K. Ahn, J. Chae, *ApJLett*, 714, L31

Statistical Distribution of Size and Lifetime of Bright Points Observed with the New Solar Telescope, 2010, Abramenko, V., Yurchyshyn, V., Goode, P.R., Kilcik, A., *ApJLett*, 725, L101

Oscillatory Behavior in the Quiet Sun Observed with the NST, 2010, A. Andic, P.R. Goode, J. Chae, W. Cao, K. Ahn, V. Yurchyshyn, V. Abramenko, *ApJLett*, 717, L79

New Solar Telescope Observations of Magnetic Reconnection Occurring in the Chromosphere of the Quiet Sun, 2010, J. Chae, P. R. Goode, K. Ahn, V. Yurchyshyn, V. Abramenko, A. Andic, W. Cao, Y. D. Park, *ApJLett*, 713, L6

Evidence of Filament Upflows Originating from Intensity Oscillations on the Solar Surface, 2010, W. Cao, Z. Ning, P.R. Goode, V. Yurchyshyn, H. Ji, *ApJLett*, 719, L194

Patterns of Flows in an Intermediate Prominence Flow Observed by Hinode, 2010, K. Ahn, J. Chae, W. Cao, P. R. Goode, *ApJ*, 721, 74

The NST - First Results and Some Lessons for ATST and EST, 2010, P.R. Goode, R. Coulter, N. Gorcex, V. Yurchyshyn, W. Cao, *Astron. Nachr.*, 331, 620

Scientific Instrumentation for the 1.6 m New Solar Telescope in Big Bear, 2010, W. Cao, N. Gorcex, R. Coulter, K. Ahn, T.R. Rimmele, P.R. Goode, *Astron. Nachr.*, 331, 636

Behavior of spines in a quiescent prominence observed by HINODE/SOT: Prominence dynamics, 2009, Z. Ning, W. Cao and P.R. Goode, *ApJ*, 707, 1124

Periodicity of Twisting Motions in Sunspot Penumbra Filaments, Z. Ning, W. Cao, P.R. Goode, 2009, *Solar Physics*, 257, 251

Investigation of Chromospheric Evaporation in a Neupert-Type Solar Flare, 2010, Z. Ning, W. Cao, *ApJ*, 717, 1232

Investigation of the Neupert Effect in the Various Intervals of Solar Flares, 2010, Z. Ning, W. Cao, *Solar Phys.*, 264, 329-344

Spatial and Spectral Behaviors of Solar Flares Observed in Microwaves, 2009, Z. Ning, W. Cao, *Solar Phys.* 257, 335 (WENDA SUGGEST REPLACING BY ANDIC IAU PAPER???)

Evidences of Chromospheric Evaporations in the December 1, 2004 Solar Flare, 2009, Z. Ning, W. Cao, J. Huang, G. Huang, Y. Yan, H. Feng, *ApJ*, 699, 15

Small-scale Oscillations in a Quiescent Prominence Observed by HINODE/SOT: Prominence Oscillations, 2009, Z. Ning, W. Cao, T.J. Okamoto, K. Ichimoto, Z. Qu, *A&A*, 499, 595

Dynamics of Vertical Threads and Descending Knots in a Hedgerow Prominence, 2010, J. Chae, *ApJ*, 714, 618

A statistical study of the relationship between the sunspot number, maximum CME speed and geomagnetic indices, 2010, A. Kilcik, V.B. Yurchyshyn, V.B., V. Abramenko, P.R. Goode, N. Gopalswamy, A. Ozguc, J.P. Rozelot, *ApJ*, in press

Variations of Current Helicity in Active Region 10930 as Inferred from Hinode Spectropolarimeter Data and Cancellation Exponent, 2010, V. Yurchyshyn, V., V. Abramenko, V., *Proc. Third Hinode Meeting, ASP Conference Series*, in press, ed. Sekii, T.

Relationship Between Earth-Directed Solar Eruptions and Magnetic Clouds at 1 AU: A Brief Review, 2010, V. Yurchyshyn, D. Tripathi, *Adv. Geosciences*, 21, 51

B. Proposed Research

The research we propose here is built on our long experience, but with the excitement and anticipation of the NST with three times the aperture of the old BBSO solar telescope and a vastly superior optical design. The NST is the culmination of a decade of re-instrumentation at BBSO. The NST is already enabling us to probe, spatially and temporally, phenomena that have been tantalizingly just beyond our grasp. Before proposing the first science that will take full advantage of the NST, we give a brief overview of the new instrumentation that will make the science possible.

B.1 Current Instrumentation Projects

B.1.1 New Solar Telescope (NST) with Adaptive Optics (AO)

The NST is a modern, off-axis 1.6 m clear aperture instrument (Goode et al., 2010b and Cao et al., 2010a), which offers a significant improvement in ground-based, high angular resolution and polarimetric capabilities. The NST project is described in detail in <http://www.bbso.njit.edu/newtelescope>.

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. The primary mirror (PM) is 1.7 m with a clear aperture of 1.6 m. 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 (FOV) of the NST. The working wavelength range covers 0.4 to $1.7 \mu\text{m}$ in the Coudé Lab one floor beneath the telescope and all wavelengths including far infrared are at the Nasmyth focus optical bench attached to the side of the telescope structure. In fact all wavelengths are also available at a focus immediately before the light is fed to the Coudé Lab. An off-axis design was chosen principally because of its vastly reduced stray light, since there is no central obscuration, which reduces the telescope's MTF (Modulation Transfer Function) at high spatial frequency.

We have designed and implemented the NST as an open telescope structure with an equatorial mount. A key design issue for a large aperture, solar telescope is the thermal control system to keep the temperature of the mirrors very close to, or below that of the ambient air. The new dome employs a wind-gate and exhaust system to control the airflow from the wind helping to maintain the same temperature inside and outside the dome, and clear concentrations of heat in and around the optical paths. It turns out that a natural circulation is setup with cool air flowing down onto the PM and heat exhausted as a plume from the high point on the wall of the mirror cell. This serves to limit "mirror seeing" by sweeping away turbulent cells and directly cooling the front surface of the PM enabling diffraction limited observations for several hours a day. The optical support structure (OSS) and active support mirror cell were built and tested by DFM Engineering in Longmont, CO. The PM is supported by 36 actuators that can bend out low-order aberrations. Alignment and first light observations were done during the winter 2008-9 with first light in January 2009. Steward Observatory Mirror Lab figured the PM.

The wavefront sensing system for alignment and active optics resides before M3. The polarization modulator also resides there. Having the modulator so far forward is a design advantage that enables us to obtain vector magnetograms, which we really were never able to do with the old 0.6 m telescope because there were always many (oblique) mirrors between the sunlight and the polarimeter's modulator.

The NST has a fully operational, nearly acromatic adaptive optics (AO) system on a vertical bench in the Coudé Lab for diffraction limited imaging, as illustrated in Figs. 1 and 3. The AO system incorporates a 97 actuator deformable mirror, a Shack-Hartmann wave front sensor with 76 subapertures, and a digital signal processor system. This is structurally the same "AO-76" used on the now-retired 0.6 m BBSO telescope and the Dunn Solar Telescope (DST) of the NSO. NST images also routinely undergo post-facto 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 larger field of view than the isoplanatic patch for most of the observational time Wöger et al.(2008). The ap-

proach 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.

The AO-76 system tracks on granulation for the NST, while with the old telescope we only able to track on pores, which reflects to some extent the problems of retrofitting an AO system on a powerful telescope that was not designed to support AO. A detailed and realistic error budget analyses (Rimmele 2008, private communication) that include AO residuals, telescope and instrument error budgets, and the steady, good (an AO correctable $r_0 \sim 6$ cm all day long, which is of granular scale so the AO can usually lock on granulation). BBSO seeing conditions measured from the ATST site survey (see <http://atst.nso.edu/site> for details) show that AO-76 will yield, in the detector plane, a high Strehl ratio of about 0.7 in the near infrared ($1 \mu\text{m}$) under median BBSO seeing conditions. However, in the visible ($0.5 \mu\text{m}$), AO-76 will deliver a sufficient Strehl (~ 0.3 , which would imply diffraction limited imaging of the solar disk) only under exceptional seeing conditions. Thus, truly diffraction limited observations will be rare in the visible spectrum, even though they would be critical for the highest possible spatial resolution. Therefore are developing, in collaboration with NSO, an AO system based on a commercially available, 357 actuator DM (AO-308), which based on our error budget analysis, we realistically expect to achieve a Strehl ratio of 0.3 in the detector plane in the visible ($0.5 \mu\text{m}$) for median BBSO seeing conditions, Rimmele (2008, private communication). The high order AO system is further motivated because polarimetric observations with low Strehl range from difficult to impossible to interpret. The problem here is that the requisite opposite polarity measurements, which are subtracted from each other, are often closely (tenths of arcsecs) spaced together. The Strehl, generally used to quantify the performance of an AO system, is the ratio of the maximum intensity in the AO corrected image in the detector plane to that from a theoretical, perfect imaging system operating at the diffraction limit.

The AO-308 project is well-underway. Under separate funding, we have purchased a 357 actuator DM from Xinetics and it has a special faceplate made of silicon instead of ULE because silicon has about 100

times the thermal conductivity of ULE to conduct away the heat on the DM from the Sun. The other elements of AO-308 are a more complex DSP system from Bittware (DSPs are about 10 times faster than those for AO-76) and a faster camera (Phantom V7.3 from Vision Research) with Quasar providing the camera to DSP and DM to DSP interfaces. Each hardware element and its connections to its partners has been successfully tested. What remains is DSP control and the GUI with the former being built on the programming from AO-76, and this is well underway. The optical design AO-308 is close to that of AO-76 requiring only the replacement of two optical elements in the AO-76 feed. We expect to test the AO-308 system in the Summer of 2011 and have full operation shortly thereafter, which is well before the funding proposed here would start.

With AO-308 feeding light to our optical instruments in the Coudé Lab, BBSO will collect a richer spectrum of data.

B.1.2 Focal Plane Instrumentation

The IRIM (InfraRed Imaging vector Magnetograph) system developed by BBSO is in operation (Cao et al., 2006, 2010b) on the NST. In addition to the line-of-site magnetogram in Fig. 3, we show a vector magnetogram in Fig. 4. IRIM is one of the first imaging spectropolarimeters working at 1565 nm, and is used for observations of the Sun at its opacity minimum, exposing the deepest photospheric layers that can be seen. IRIM is a tandem system, which includes a 2.5 nm interference filter, a unique 0.25 nm birefringent Lyot filter, and a Fabry-Pérot etalon. IRIM is capable of providing a bandpass as low as 0.01 nm in a telecentric configuration. IRIM benefits from our AO-76 system that have been adapted to the NST. The light for the AO and IRIM is fed through the telescope's polar axis to the temperature controlled Coudé Lab on the floor beneath. The temporal cadence of the IRIM magnetograms is 30 s, but it will be about five times faster when the Lyot filter is replaced by a second Fabry-Pérot filter in the Spring of 2011, so the second generation IRIM will be available well before the work proposed here would begin. The first imaging polarimetric observations at 1565 nm were made at the diffraction limit on July 1, 2005 using BBSO's old 0.6 m telescope (Cao et al., 2006). Stokes-V profiles were obtained from the Fabry-Pérot etalon scan,

Table 1: Milestones in NST Commissioning.

Date	NST Milestone	Observations	Reso
Summer 2011	AO-308 Installation on NST	Diffraction Limited in Visible	
Spring 2011	IRIM Upgrade to Dual Fabry-Pérot Etalon System	Vector Magnetograms in NIR	0.2''
Fall 2011	VIM Installation	High Spatial Resolution Vector Magnetograms	0.1''
Summer 2013	First Observations with MCAO	AO Corrected Light over Full FOV	0.05''
Fall 2013	CYRA First Light	Spectrographic Observations Covering 1.0-5.0 μm	0''.1-

and the data provide access to both the true magnetic field strength and the filling factor of the small-scale magnetic flux elements. The strength of IRIM is its extreme sensitivity and high spatial resolution, which allows us to study weak and small-scale magnetic fields in the quiet Sun. One might think that the quality of magnetograms from the NST with triple the aperture of the old telescope would be compensated by roughly tripling of the wavelength of observation. However, Zeeman splitting increases quadratically with wavelength, so IRIM can more precisely detect magnetic flux. Second, we will now be able to extract the true magnetic field strength and the filling factor for the small-scale magnetic flux elements (Cao et al., 2006). Third, the terrestrial atmosphere is more benign in the NIR with the mean Fried parameter at BBSO being about 25 cm (under the assumption of Komolgorov turbulence), which is four times that at 0.5 μm . Even with AO-76 corrected light, this much larger Fried parameter is essential in the observations of faint features, which otherwise would tend to drift in and out of sharpness. The Fried parameter, r_0 , is the coherence length of the atmospheric turbulence. For telescope apertures larger than r_0 , resolution is seeing limited. The focal plane Strehl in the NIR is sufficient to enable sustained diffraction limited images with AO-76 under typical BBSO observing conditions, but images at 0.5 μm would only be diffraction limited under extraordinary seeing conditions at BBSO. For this reason, we are planning AO-308, which will enable diffraction limited imaging in the detector plane in visible light under nominal BBSO seeing. For the work proposed here, we will have AO-308 and VIM for science that requires vector magnetograms of the highest spatial resolution (0''.1) with the sacrifice being the difficulty of obtaining sustained results under ordinary seeing conditions.

The weakness of IRIM is the spatial resolution, but

this problem will be solved using our Visible Imaging Magnetograph (VIM) that was in use on the old BBSO telescope (Denker et al., 2007) and obtained photometric data and magnetograms. IRIM and VIM have the same basic design and operational modes and both magnetograph systems were ready to be integrated into the NST at first light, but since diffraction limited operation of VIM will require AO-308, we chose to bring IRIM on line first.

To better understand the fine structure of the solar chromosphere, NST is equipped with a Fast Imaging Solar Spectrograph (FISS REFERENCE???)?. This is a field-scanning slit spectrograph with high spectral resolving power (1.4×10^5) 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 μm — 0.92 μm). The major spectral lines of interest for studying chromospheric dynamics are $\text{H}\alpha$, 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.(NEED TO GIVE A SCIENCE REFERENCE TO FISS???)

We have programmed a 32-node parallel computing cluster, so that we can perform real-time speckle reconstruction with a cadence of about 1 minute (for a $1\text{k} \times 1\text{k}$ camera)(NEED TO CHECK THIS???)?. At present, we use this system for speckle reconstruction of each days data, so there is no backlog in data reduction.

In collaboration with the National Solar Observatory (NSO) we are developing a Multi-conjugate Adaptive Optics (MCAO) system for the NST that

will expand the field of view (FOV) of diffraction limited observations by about an order of magnitude to at least 1 arcmin. The expansion of the diffraction limited FOV will be sufficient to cover entire active regions enabling spectroscopic and polarimetric observations, which include, for instance, flares that may occur at anytime and anywhere in an active region. Therefore, the MCAO system will eliminate a major limitation of conventional AO systems, the insufficiently large isoplanatic patch, and, thus provide the tool to effectively study, with unprecedented spatial and temporal resolution, fundamental scientific questions like the onset and evolution of flares, flare triggering mechanisms, magnetic reconnection events and many other dynamic solar phenomena that would be best performed with diffraction limited observations over an extended FOV with the requisite high temporal cadence. It is not clear that MCAO will be on-line before the last year of the work proposed here, so we don't count on MCAO (CAN WE SAY SOMETHING MORE OPTIMISTIC??). Rather, for slow (about 5 s) cadence we will use AO combined with speckle reconstruction, while for appreciably higher cadence we will suffer the the gradual roll-off in resolution as we move further from the isoplanatic patch. Of course, the NST is a 2 m² "light-bucket" that can be used to accumulate sufficient photons for very high temporal cadence observations of rapid phenomena in visible light, as well as in the NIR.

The CrYogenic infRARED Spectrograph (CYRA) spanning 1.0 to 5.0 μm will help the NST achieve its scientific potential of probing for the first time the fundamentals of the Sun's atmosphere with its dynamic magnetic field, the origin of space weather. CYRA will be a substantial improvement over the two current solar IR spectrographs – one operating at the National Solar Observatory (on the McMath-Pierce telescope) and the other at Institute for Astronomy (Mees Solar Observatory, University of Hawaii), both of which are based on warm optics except for the detectors and order sorting filters. CYRA will be a significant advance, particularly for high-spatial and high-cadence and high Zeeman sensitivity observations of the Sun's atmosphere from the photosphere through the chromosphere, as well as observations of dimmer targets such as sunspot umbrae and off-limb features. (MORE SCIENCE, ESPECIALLY CORONAL FIELDS??) We don't propose to use CYRA here be-

cause we expect it to be on-line late in this three year proposal.

B.1.3 Milestones in the Commissioning of the NST

We are well into the commissioning phase for the NST. We have the NST delivering diffraction limited images after correction by AO-76. We are making photometric observations in visible light and have vector magnetograms in the NIR. We expect AO-308 will be on-line well before the 2012 observing season. None of what we propose here relies on MCAO or CYRA observations. Table 1 lists the remaining milestones of NST commissioning, and corresponding scientific observations that are germane to this proposal.

B.2 Proposed Scientific Research

(COMMENT: INSTRUMENT SECTION IS PROBABLY TOO LONG LEAVING TOO LITTLE ROOM FOR SCIENCE PART. SCIENCE PART DOESN'T EXIST YET. PART A IS PROBABLY TOO LONG AS WELL??)

Each proposed scientific research task takes advantage of one or more of the NST's unique attributes, which include high spatial and temporal resolution, precise measurements of vector magnetic fields and observations of faint features. We will probe what has been just beyond our grasp, but build on our earlier research. The proposed research is also very timely, as NASA missions Hinode, SDO and STEREO are operating. Joint observations between NST and these satellites will produce unprecedented scientific returns.

At 1.6 μm , where the IRIM is designed to utilize the two strong magnetic lines, the NST will have a spatial resolution of about 0.2'', while VIM will have three times the spatial resolution.

Although our research goals are mainly based on high resolution observations with the NST, BBSO will continue to provide synoptic observations in full disk H α to support NASA missions. Because of the NST, the BBSO H α system has been moved permanently under a separate dome, which is very close to the NST dome. This opportunity allowed us to modernize the optics and camera system yielding a new H α telescope in BBSO, which is fully remote-control, including setting an arbitrary order of wavelength shifts

in advance. The full disk observations are complementary to high resolution observations, in particular when studying the large-scale structure of flares, filaments and CMEs.

B.3 Topics

(NEED TO CONNECT TO NASA DATA AS POORLY SKETCHED IN PROJECT SUMMARY???)

Vector fields in quiet Sun to resolve the Hinode "myth". As granules rise and BPs appear what happens to the local field.

As the observational evidence is solid and data analysis/modelling tools are mature, the scientific objective of this part of the proposed research is straightforward: to understand the physics of the observed magnetic field changes. For this, one requires high-cadence, high-resolution and highly stable vector magnetograms. Obviously, due to the stability of the terrestrial atmosphere and line formation height in the lower photosphere at wavelengths near the opacity minimum at $1.6 \mu\text{m}$, IRIM on the AO-76 equipped NST will be ideally suited for the purpose of probing the underlying physics of magnetic field changes arising from impulsive events. Depending on the number of spectral positions chosen for the line scans in IRIM operations, we will have as short as a 30 S cadence for vector magnetograms. The expected polarization accuracy will be our nominal 10^{-3} . The spatial resolution will be around $0.2''$ for direct imaging, and $0.4''$ for magnetograms. Using the well-calibrated IRIM data, we will target the following two topics that we couldn't address before (NOTE: TOO MUCH IRIM NOT ENOUGH VIM???): (1) the full 3-D structure vector magnetic fields after correction for geometric projection; (2) the spectroscopic properties of the areas undergoing rapid structural changes to reveal the temperature and density changes. Joint Hinode/NST observations will be complementary in this study: NST observes magnetic fields in the NIR, while Hinode operates mainly in the visible; the NST has a much larger aperture, while Hinode has continuous seeing-free coverage. The high-cadence observations from the Hinode filtergraph observations are essential to detect and characterize the rapid structural changes in sunspots. However, Hinode has some technical difficulties that preclude vector magnetograph observations at this writing (STILL TRUE???). On the

other hand, analyzing lower-cadence Hinode spectro-polarimeter observations will enable us to study spectral line profiles in the areas that sustain structural changes. Therefore, we can come to understand more detailed physical characteristics (e.g., temperature, density and more accurate polarimetry) of the rapid changes in active region structure associated with flaring.

(DELETE MUCH OF THE NEXT PARAGRAPH???) To observe these flows and magnetic field structures in detail and to understand their fundamental nature, we need high-resolution and high-cadence observations. Obviously, the AO equipped NST will attain the required high resolution of order of $0.2''$ in the NIR, lasting all day long for typical BBSO days. In our planned studies, we expect to answer the following questions: (1) Do active regions always show changes in flows associated with flaring as discussed above? What are the spatial distributions of the flow evolution? (2) Are shear flows unusually strong before a major flare, and spatially located close to the flaring neutral line? What are the physical implications of shear relaxation on large-scales and shear increase in a small area near the flaring neutral line (Wang, 2006)? Again, observational results will be compared with flare/CME models that require formation of sheared magnetic fields by shear motion, such as the breakout model (Antiochos 1998; Antiochos et al. 1999). Complementary to high resolution with high temporal cadence NST NIR flow data, Hinode data will provide high polarization accuracy, while SDO will provide full disk coverage with vector magnetograms to allow continuous monitoring of all the active regions on the disk.

B.4 NST Data Online

Figure from Vasyl and some discussion.

C. Personnel and Management

To develop state-of-the-art instrumentation and carry out pioneering research with our precious resources, we must have balanced, first-class instrumentation and science teams. Three BBSO researchers (Goode, Cao and Yurchyshyn) will have their own distinct, but linked responsibilities (see Table 2). The research and

Table 2: Role and Tasks of Team Members.

Name	Role	Tasks
Goode	PI	Overall Supervision and NST Development
Yurchyshyn	Co-I	Coordination of Scientific Projects
Cao	Co-I	Focal Plane Instrumentation
Lim	Post-doc	Small-Scale Photospheric and Chromospheric Dynamics
Varsik	Computer Engineer	Active Region Flows and Quiet Sun
Fear	Senior Observer	NST Observations
Graduate Student Zhideng Zang		Flare Studies
Nenow, Shumko, Abramenko	Staff	Instrumentation

instrumentation teams are also identified in the table. What we propose is based on the NST scientific instrumentation that is already operating, and we can perform nearly all we propose even without AO-308 and VIM – in that unlikely event of AO-308 being implemented in the second year, rather than nearly a year before the Summer of 2012. What are problematic are MCAO and CYRA, so we have proposed nothing using them.

Figure 4: Vector magnetogram from IRIM observations with AO-76 on the NST. The spatial resolution is about $0''.4$. The temporal resolution is about 30 s. MORE DETAILS

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