63-Inch Solar Telescope in Big Bear

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ABSTRACT:

We plan to build a 63-inch aperture solar telescope at Big Bear Solar Observatory (BBSO), which would be the world's largest aperture solar telescope. Here we propose for support to purchase, polish and mount the primary, a secondary, a heat stop and a tertiary mirror. We have identified all three blanks. The new telescope will adopt an open Gregorian design, and will be combined with our adaptive optics system, and will take advantage of the excellent seeing conditions at BBSO. The diffraction limit of the telescope is about 50 km at 5000 Å. We plan for first light in early 2006.

The new telescope will not only be used as a new powerful scientific instrument, but at the same time, it will be a test-bed for the following generation solar telescope: the planned 4-meter Advanced Technology Solar Telescope (ATST). Scientifically, the 63-inch telescope will enable us to make breakthroughs in the following research areas: the fine structure of solar flares; the structure and evolution of magnetic fields in flaring active regions; the dynamics of kilogauss fluxtubes; magneto-convection in sunspots and the heating of the upper atmosphere. In addition, the telescope will be used at night to study the spectrum of the earthshine by observing the moon. The earthshine provides a way to measure the large-scale structure, composition and evolution of the earth's atmosphere, including that of the greenhouse gasses.

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A Overview

The highest resolution solar telescopes currently operating have diffraction limits only allowing them to resolve features larger than 100 km in size on the sun, and are often photon starved in the study of dynamic events because of diffraction limited spatial resolution, short exposure times to minimize seeing effects, and high spectral resolution to resolve line profiles. Thus, understanding many significant solar phenomena remains tantalizingly close, but just beyond our grasp. With a 63-inch telescope (at an excellent site, outfitted with Adaptive Optics (AO) and the latest detector systems), one would be able to significantly and fundamentally advance our knowledge of the nature of the dynamic sun. The observed magnetic field of the sun is composed of conglomerations of individual fibers of the field, which are generally thought to have cross sections of order 100 km. With the aforementioned 63-inch telescope, we could probe the fibers, and the interfaces between them when they are bundled, and determine the size distribution of the fibers. Understanding small-scale solar activity is at the heart of understanding large-scale solar activity. As for the dynamics, it is critical to resolve the structures within emerging active regions, small-scale motions around the fibers (or "fluxtubes", as they are also known). Further, what is the nature of ephemeral regions? Why do sunspots form, and what is their structure and dynamical nature? What are umbral bright points? What is the character of the penumbral magnetic layers and the flows of adjacent fluids? What is the fine structure of flares and their relation to coronal mass ejections (CMEs)? How do flares and CMEs, and the areas around them, evolve? Why are there so many kinds of flares? How do all these phenomena vary with the solar cycle? With these, and other unsolved problems in mind, we propose to replace BBSO's 26-inch telescope.

Hardware	Cost [K$]	Vendor	Delivery Date
63-inch primary blank (plus secondary)	60	CrAO	June 2003
Polishing of primary and secondary	300	Brashear	June 2004
Flat Mirror (polished) and Heat Stop	15	CrAO	July 2004
Telescope Structure	95	Brashear	January 2005
Mirror Cells	100	Brashear	January 2005
Assembly and Alignment	30	Brashear	June 2005
Total for Optical Hardware	600		June 2005

Table 1: 63-inch telescope polished optics, including housing, assembly and alignment

We plan to build a 63-inch (precisely 1.6 meters) aperture telescope at Big Bear Solar Observatory (BBSO). This would be the world's largest aperture, high resolution solar telescope for study of the sun in visible and the infrared. Here, *we propose for support to purchase and polish a particular 63-inch mirror blank, the associated secondary, heat stop and flat mirror, and incorporate them into a mounting.* We have identified the mirror blanks that are ideal for our purposes. The budget for this phase of the project is given in Table 1. The primary and secondary blanks, as well as the heat stop and polished flat mirror, will come from the Crimean Astrophysical Observatory (CrAO) in the Ukraine. The mirror blanks are made of Citall (extremely low thermal expansion glass of the highest quality), and are ready so that we don't have to wait a year or two for the annealing of the glass for the primary. The blanks will be shipped to the US, where the remainder of proposed the work will be done by Brashear LP (well-experienced in working with Citall and makers of the USAF 3.67 m Advanced Electro-Optical Telescope atop Haleakala in Hawaii). We expect the project to begin early in 2003. The second phase of the project includes the mechanical system ($400 K), the control system ($200 K), the retractable dome ($150 K), and final installation ($150 K). We have identified $500 K of this second, $900 K phase. Our university, New Jersey Institute of Technology (NJIT), will contribute $500 K, which is money it has already agreed to fund equipment matches to our existing NASA and NSF backbone grants, which support BBSO. We will seek the remainder from federal funding agencies. This new telescope will utilize the leading-edge instrumentation developed, in part, from prior DoD support to make unique high resolution studies of the sun. High resolution studies of the sun and its magnetic field are at the frontier of efforts to understand the nature of our variable star and its effects on human technologies. We plan for first light in early 2006.

Until recently, high resolution studies of the sun were limited because adaptive optics systems were unavailable for solar telescopes. At the heart of the problem in studying the sun, which is an extended source, was the apparent lack of a guide star, as used in night time astronomy. Even using the granular field of the sun as a "guide star" was not possible because of the lack of fast and sensitive deformable mirrors, wavefront sensors and cameras. Recently, a low order system has been built at the National Solar Observatory (NSO), Rimmele et al. (1999). Formerly, Rimmele was a postdoc in the NJIT group, and our working relationship with him remains close. In collaboration with Rimmele, we are currently building two high order adaptive optics systems – one for BBSO and one for NSO. The initial tests of the first of the two high order systems will occur this fall. The BBSO high order system will be used on the proposed 63-inch telescope. As part of the BBSO effort in adaptive optics, we have assembled here in Big Bear a team of experts with long experience building instrumentation. This team will also comprise the core of our effort to implement our 63-inch telescope and feed its light to our state-of-the-art instrumentation. The NSO adaptive optics system is also meant to be a prototype for a still higher order system for the 4.0 meter Advanced Technology Solar Telescope (ATST), which has been strongly supported in the NAS/NRC Decadal Survey (Astronomy and Astrophysics in the New Decade, 2001). Further, NSF-Astronomy has funded the design and development phase for the ATST. NSO is just beginning the site survey process, while they lead the effort to identify what instrumentation would be needed. One would be quite optimistic in assuming 2012 as the time of first light, with 2015 being more reasonable. It could well be that this was part of the reason that an earlier NAS/NRC study (Ground-Based Solar Research: An Assessment and Strategy for the Future, 1998), the so-called "Parker Report", urged building an intermediate aperture solar telescope first, like the one we propose. Such a telescope would be a test of the technologies and could be done much more quickly. We plan for first light early in 2006 for the BBSO 63-inch telescope. Of course, this telescope would be of great scientific benefit and would likely dominate ground-based solar astronomy for a decade. Further, such a telescope would be well-positioned to support NASA missions, such as the Solar Dynamic Observatory (SDO) scheduled for launch in 2006, with a three year planned lifetime. It will also provide critical, complementary data for two other upcoming space missions designed to study the sun and its extended atmosphere – the Solar TErrestrial RElational Observatory (STEREO) and Solar-B.

BBSO is an ideal site for ground-based NASA-like campaign-style observations because it is characterized by excellent "seeing" conditions all day long. The atmospheric turbulence that degrades images ("poor-seeing") comes primarily from two atmospheric layers – near the ground and at the level of the jet stream. BBSO is situated high (7,000 ft) in a mountain lake in the cloudless mountains of southern California. It is an ideal site for daytime astronomy. BBSO's dome is located at the end of a 1000 ft long causeway jutting into the lake. The lake, with its cool waters, provides a natural inversion, and the dome has two miles of open water to its west. Since the prevailing winds are from the west, the ground-seeing problem is largely eliminated, Goode et al. (2000), and the wind comes to us in a nearly laminar flow. Another factor for the good seeing might be the east-west orientation of the Big Bear Valley acting as a wind channel. Further, since we are relatively close to the ocean, turbulence from the jet stream layer is reduced because the jet stream is calmest over the oceans.

NJIT took over operation of BBSO on July 1, 1997. Since then, we have produced over 130 scientific papers. At present, BBSO is one of two solar observatories in the US with a telescope, instrumentation and a site that enables high resolution studies of the sun at the present frontier (sub-meter class telescopes); the other is the NSO with the Dunn Solar Telescope (DST). Due to the broad and important community service mission of NSO, BBSO is the only one that can work in sustained campaigns – essential for the broadly-based, high resolution observations needed to gather unique data to understand the fundamental nature of solar magnetism and its evolution. Our capability of running sustained campaigns is at the core of our ability to provide unique support to satellite programs to study and understand the sun. Since 1997,

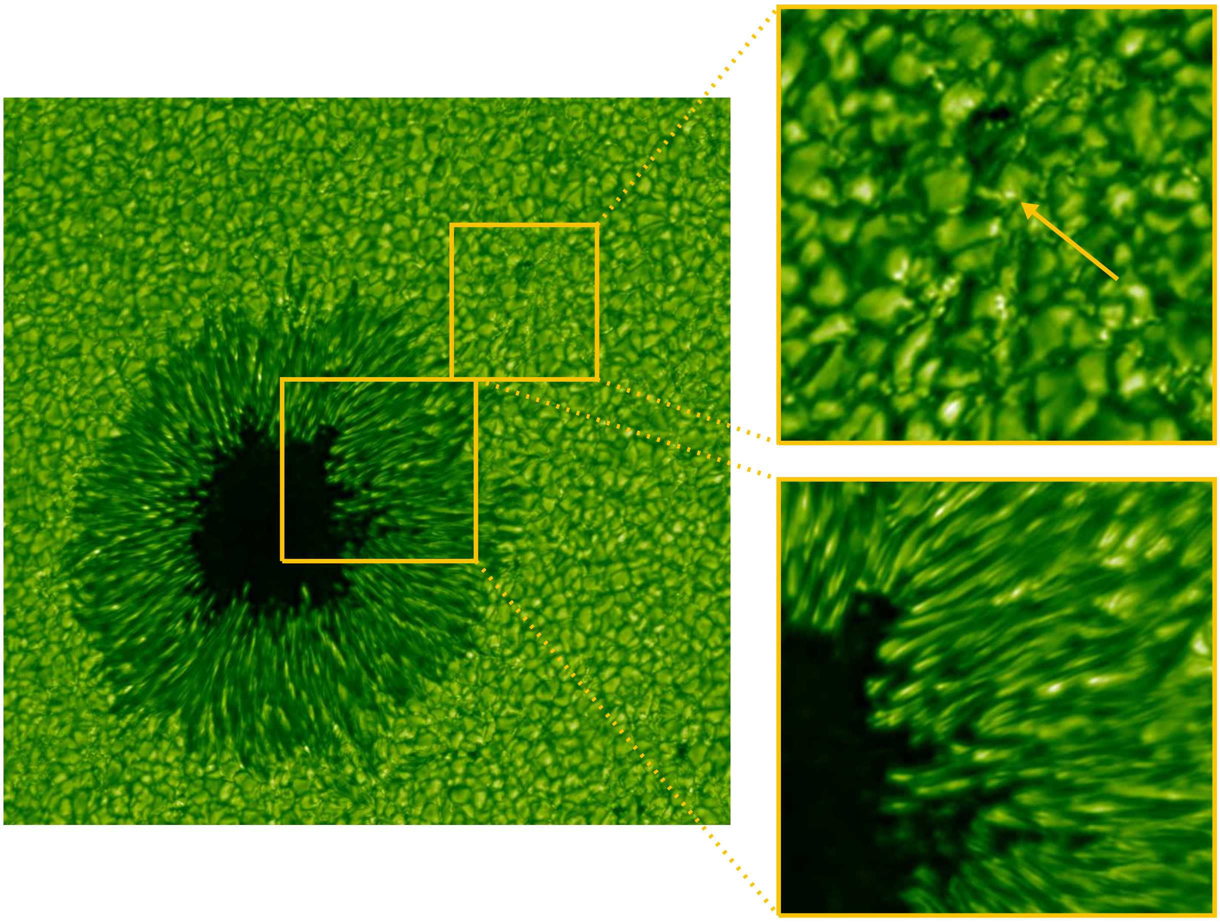

Figure 1: Image of a sunspot (NOAA 8673) taken on August 27, 1999 (520 nm with a $76'' \times 76''$ field-of-view) with the characteristic black umbral center and the penumbral fibers. Also shown are parts of the granular field as an inset. The bright points in the intergranular lane, like the one indicated by the arrow in the upper right panel, are at the diffraction limit of the telescope.

we have made fundamental changes in the observatory's instrumentation, which should ensure a unique and significant scientific role for BBSO. The advances in instrumentation were critical for improving the quality of our observations, especially for high resolution studies. Here, we propose to take the last major step in this development effort – a 63-inch telescope feeding all of the instrumentation we have developed.

The support at NJIT for our program remains strong. In the last year, NJIT has supported the expansion of our group to include a fourth, regular tenure-track faculty member; Carsten Denker became an assistant professor starting with the Fall 2001 semester. We have our team in place to do the work that we propose. The team includes optical, mechanical and electronics engineers. Further, this team includes students who are the future of our scientific and instrument building program. We believe that building and implementing our 63-inch telescope will be a bridge to the future of solar astronomy in the US. The telescope, and its attendant instrumentation, will provide many new and unexpected scientific results. This will help to draw the best students into the field, and keep the field alive and vital. These students will be the true beneficiaries of the ATST, and vice versa.

BBSO highly prizes its special role in the education of the next generation of scientists who build instruments. We graduated 4 Ph.D. students in 2000 and 2001. We currently have 11 Ph.D. students (8 men and 3 women), and 3 of the 11 will graduate in 2002. Generally, each student builds the additional instrumentation necessary for his/her Ph.D. work. This broadens the education of the student, while strengthening the observatory. The typical new instrument needed by a solar observatory constitutes a small enough project, so that one graduate student can handle all aspects of its development. Our typical student will receive a Ph.D. in Applied Physics, Electrical and Computer Engineering or Computer Science. Such training prepares our students for a scientific career, while ensuring broader career opportunities. Our most recent graduate is now leading an infrared (IR) optics group in a New Jersey company.

To appreciate the resolution that our 63-inch telescope would provide, in Figure 1, we show a high resolution image of a sunspot taken on August 27, 1999 with our 26-inch telescope. In the figure, one can easily identify the dark umbra of the sunspot and the daisy petal-like penumbral fibers. In the inset on the lower right the transition from the penumbral structure to the granular field is apparent. In the lower right panel, one can see the granular field, and an occasional bright point in the lanes. The bright points are at the diffraction limit of the 26-inch telescope. These points are the fundamental fibers of the field (fluxtubes) , or aggregates thereof, and with the 63-inch telescope we will be able to resolve them, and gain clarity on the fundamental nature of the solar magnetic field. In detail, the 63-inch telescope would be able to resolve features on the solar surface down to 50 km in size. Since the fluxtubes are 100 km sized objects, we will be able to probe them in a way that has never been done. A 63-inch telescope in combination with AO enables us to do spectroscopy/polarimetry with essentially diffraction limited resolution!

B The 63-Inch Telescope

B.1 Technical Overview

The 63-inch telescope will have an open design (see Figure 2, which shows the layout of the open telescope including its retractable dome). The telescope will utilize the current pedestal of BBSO's 26-inch telescope. However, the dome will be removed and replaced by a retractable one. We list the main features of the telescope below:

- 63-inch aperture
- Gregorian configuration (four mirrors – parabolic primary, heat stop, elliptical secondary and diagonal flat) with cooling systems
- Open telescope tube with equatorial mount, fully retractable dome
- Computer controlled pointing and tracking
- Adaptive optics
- Multiple focus locations that serve a variety of focal-plane instrumentation.
- 3 arcmin field-of-view
- 32 m effective focal length with a final ratio of f/20.0
- Wavelength range from 0.39-2.0 μm with AO
- All wavelengths >0.39 μm on additional optical bench without AO
- High resolution of $0.07''$ at 500 nm and $0.21''$ at 1,565 nm (with adaptive optics)
- Fiber optic spectrograph for observing the earthshine spectra into the IR.
- Temperature monitoring at many points on the telescope
- Telescope optics will be made of Citall (CO-115m). Primary mirror will be parabolic and secondary elliptical

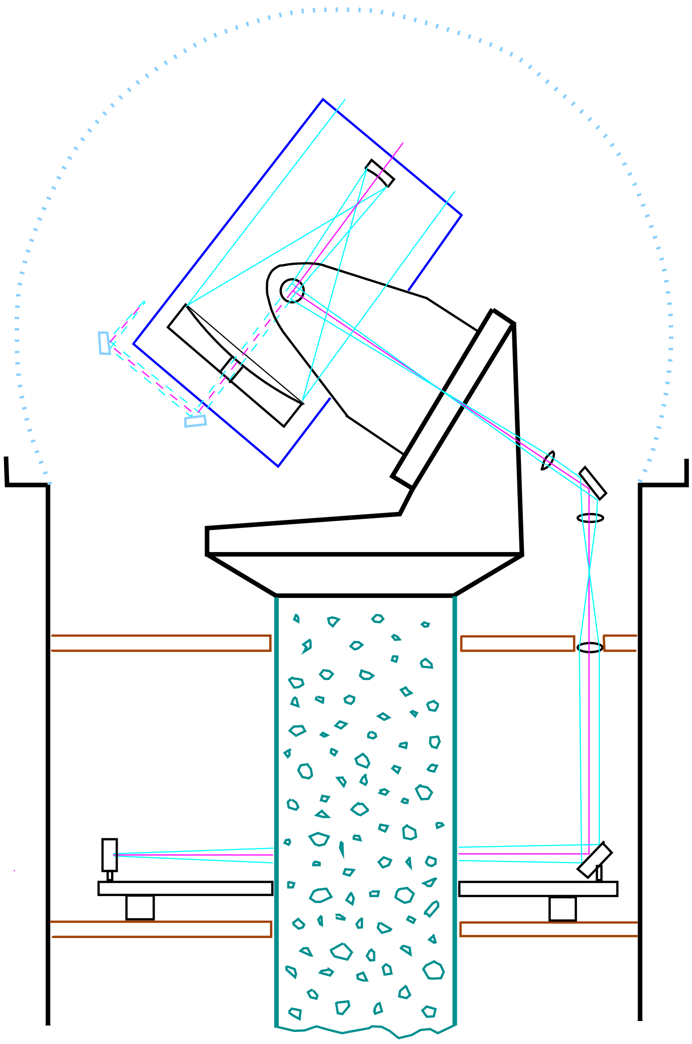

Figure 2: Schematic of the new open telescope and the retractable dome (not to scale), including the light path to the primary post-focus instrumentation on the floor below the telescope. The additional optical bench, for observing a wide spectral range, is fixed to the telescope. This bench is accessed through the hole in the primary and two flats when the diagonal flat mirror is flipped out of the optical path.

There are two key design issues for a large diameter open solar telescope; the first is keeping the temperature of the mirrors the same as the air, and the second is polishing the primary and secondary to high optical quality. For controlling the temperature of the mirrors, the mirrors will have a high reflectivity coating, and we will use four high-precision cooling systems for M1, HS (heat stop), M2, M3 (see Figure 3). The back of the mirrors will be cooled using circulating alcohol, while the front of the mirrors will be cooled by using laminar airflows.

The success of the Dutch Open Telescope has been lauded in the Parker Report; in particular, relying on the wind to limit so-called "mirror seeing". In addition to the effects of atmospheric turbulence, solar telescopes suffer from the heating of the optics by sunlight. These cause the image to shiver and become blurred. Modern solar telescopes are either vacuum telescopes (like BBSO's 26-inch telescope), and/or use careful control of the temperature of the optical elements to reduce heating of the air in the telescope. Vacuum telescopes cannot be built with large apertures because such a design requires a vacuum window

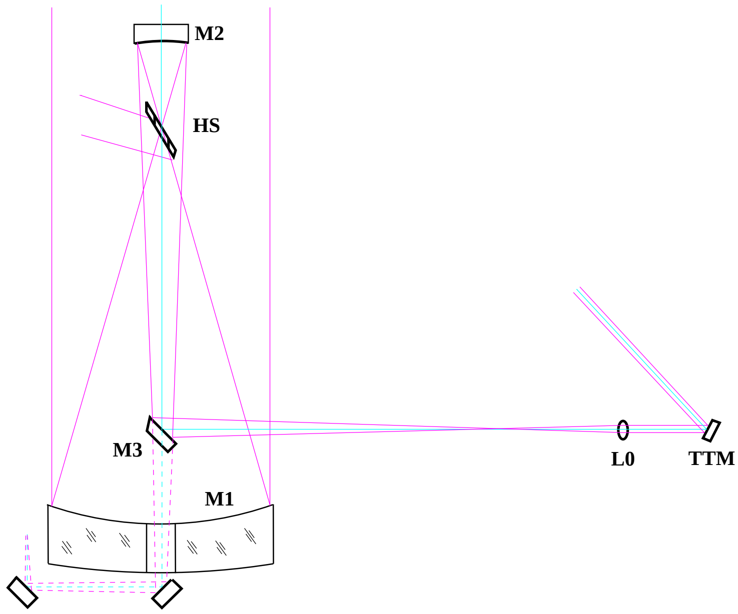

Figure 3: The optical path of the telescope (not to scale). The f-ratio of the primary is 2.5. The telescope's effective focal length is 32 m. The final ratio is f/20 with an image scale of 6.4″/mm. The exit pupil diameter is 261 mm, and it is located 776 mm behind M2. To obtain the highest possible resolution, the optical train will be diffraction limited. This means that the primary mirror M1, the secondary mirror M2, and the flat mirrors (M3 and TTM) will be polished to an rms precision of $\lambda/15$ at 633 nm. L0 is a re-imaging lens bringing the pupil to TTM. TTM is the tip-tilt mirror (same as TTM in Figure 5) to direct light to the second floor through the adaptive optics system to the post-focus instruments (PFI). For studies in the far infrared, M3 is flipped out and the light goes through the hole in the primary to an additional optical bench fixed to the telescope.

of extremely high optical homogeneity, one that is as large as its aperture. In particular, a host of problems arise because of the thickness needed to withstand the enormous difference in pressure between the air and the inside of the vacuum window. In detail, it is difficult to design a vacuum telescope, if the aperture is larger than 1 m. This is the fundamental reason why the new Swedish Vacuum Telescope will have a 1 m aperture. Our 63-inch telescope has been designed to be a completely open telescope with a retractable dome, to avoid internal seeing. The ATST will also have an open design, so that project will benefit from our experience.

The open design requires a stiff construction. Care will to be taken to protect the telescope from dust, and to enable it to withstand strong winds. Our typical winds are westerly at 10 km/h, and this is the condition under which we have the best seeing. If we want to operate the open telescope optimally, the key point is to keep the temperature of the mirror the same as the air.

B.1.1 Optics

The telescope will use a two mirror Gregorian configuration, see Figure 3, with an f/2.5 primary mirror (M1), whose shape will be parabolic. A tilted, cooled heat stop mirror (HS) at the primary focus will reject 98% of the light out of the telescope. HS will have a 3 arcmin diameter hole to pass light to M2. M2 will be a concave ellipsoidal secondary mirror. Next, the light from M2 will be reflected out of the telescope axis by a flat mirror M3 to the polar axis. After the primary focal plane, lens L0 is installed to transfer the pupil onto TTM, which delivers the light to the optical laboratory on the floor beneath.

B.1.2 Mechanical Structure

We will use an equatorial mount for the 63-inch telescope, because it allows an optical design with only three mirrors to bring the light to the TTM. Equatorial-type telescopes can be lightweight and well-balanced. Its total weight will be about 5 tons, which is less than the telescope weight presently supported by the pedestal, which includes a heavy vacuum tank. The main problems for the mechanical structure of this telescope would arise from insufficient stiffness, and deformation by temperature changes. We have considered these problem seriously, and will use an Invar structure in key parts of the telescope, so that the telescope support structure's absolute distortion will be less than 10 μm. Also, we will use cooling systems to maintain fixed temperatures in key parts that face the sun during observations.

B.1.3 Control System

We will use a Linux-based PC to control the telescope, and use a DC motor to drive the telescope and guider for tracking. The absolute encoder will be adapted for precise pointing. There are four high-precision, temperature controlled systems for the four mirrors (M1, HS, M2 and M3) with precision temperature control. There are three delicate temperature control systems for the other components of the telescope, which are needed to reduce thermal effects, with a temperature control precision that will be $\pm 0.3°$ C. More than sixty temperature monitoring points will be utilized in the telescope to estimate the performance degradation by temperature fluctuations. The main control computer can exchange data with both its serial and parallel ports. Some of the details of the mechanical performance are:

- Range of Motion:
  - RA axis $\pm 180°$ (south is origin)
  - DEC axis $+10°$ to $+80°$
- Speed range:
  - RA axis $1''$/s to $1°$/s
  - DEC axis $1''$/s to $1°$/s
- Pointing accuracy:
  - $5''$
- Tracking accuracy:
  - $1''$/5 min (without sun guiding)
  - $1''$/10 min (with sun guiding)

C Adaptive Optics at BBSO

The proposed 63-inch telescope will enable us to solve many of the outstanding problems in solar physics, especially those requiring higher resolution studies of the sun than are currently possible. As well, the telescope will occasionally function as a "light-bucket" collecting photons for higher temporal cadence, lower spatial resolution observations. However, the key to many of the most intriguing questions lies in observations with the highest possible spatial resolution. Not only does one require a large aperture telescope and a site, like BBSO, where adaptive optics can correct images to the diffraction limit, but we also need a high order adaptive optics system. NSF-ATI has funded the construction and implementation of two high order systems (97 actuators) – one at BBSO and one at the DST of NSO. The BBSO system will be used for the 63-inch telescope after upgrading the deformable mirror system.

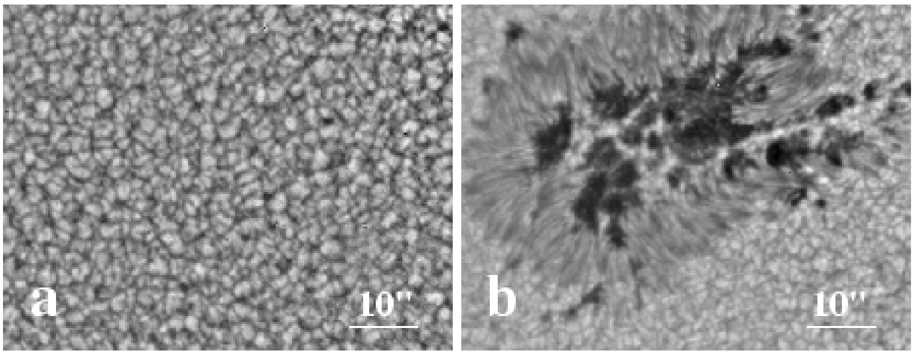

Figure 4: Unprocessed, single exposure (0.13 ms) IR images of the quiet sun and a sunspot region, demonstrating our excellent image quality.

The need for adaptive optics is made clear by considering the Fried parameter (roughly speaking, the largest aperture telescope that would be diffraction limited) at even an excellent daytime site, like BBSO. A good site has a Fried parameter of about 10 cm in visible light (500 nm). At BBSO, we sometimes have upwards of 20 cm. As good as this might be, it is small compared to a 63-inch aperture. This problem can be partly solved by post-facto image reconstruction, as discussed here in Section D.3. We estimate that under our typical good seeing, we will correct to a Strehl ratio (intensity ratio of corrected image to the true diffraction limited image) of about a steady 0.6 in the middle of the visible spectrum, which bodes well for the adaptive optics system maintaining "lock',' so that we will have steady diffraction limited observations. Once the upgraded AO system is working in the visible, the IR performance should be even better since the Fried-parameter r_0, the isoplanatic angle θ_0, and the Greenwood time delay τ_0 scale with $\lambda^{6/5}$ and the number of control parameters of the AO system even scales with $\lambda^{-12/5}$, implying that the Fried-parameter is of order $r_0 = 40$ cm at 1,565 nm, the Strehl ratio is significantly higher than in the visible, and we have evidence in short-exposure, frame selected NIR images that the isoplanatic angle can exceed $80''$, see Figure 4. In summary, with the AO system working, we might be able to correct the full FOV of $180''$ of the 63-inch telescope in the NIR at 1,565 nm without the need for multi-conjugate AO. For studies in the far infrared, we note that for a wavelength of 5μm, the anticipated Fried parameter is comparable to the telescope aperture, obviating the need for AO (see Figures 2 and 3).

At BBSO, we have completed the design of our AO system (Didkovsky et al., 2002), and expect it to begin functioning within a year and a half for the 26-inch telescope. For the 63-inch telescope, we will have to only slightly modify the light feed, and possibly upgrade the deformable mirror (DM) system. We estimate this downstream cost to be about \$300 K. The light from the telescope is fed to the optical laboratory on the floor beneath the telescope. Here, we give some details of the system, and show its optical layout in Figure 5. As designed, the system uses a small, elliptically shaped (a =45 mm, b =25 mm) Tip/Tilt mirror installed at the end of the existing coudé optical path, and a DM with a sufficient number of subapertures installed together with wavefront sensors (combined fast correlation tracker and Shack-Hartman sensors) with scientific channels (visible and IR, called SC1 and SC2 in Figure 5) on the optical tables. The two-axis Tip/Tilt platform has a resonant frequency around 3.3 kHz and tilting range of about 2 mrad, which corresponds to about $25''$ in the sky. With 32×32 pixel frames, the correlation tracker sensor can detect 2 kHz differences between a reference frame and real-time frames. The WFS channel will use either a 260×260 pixel Dalsa camera, or a 1280×1024 Photobit camera (2 by 2 binning), with a frame rate of more than 2000 frames/s for detecting high-order atmospheric abberations of the wavefront. Both scientific channels will utilize Fabry-Pérot etalons (FP1 and FP2) in telecentric configurations for imaging polarimetry (magnetographs). The optical design for these channels allows using small aperture prefilters (interference or Lyot) and 70 mm diameter Fabry-Pérot etalons with field-of-views about $180''$ (IR) and $170''$ (visible), respectively. The visible and IR imaging magnetograph channels with spatial resolution of

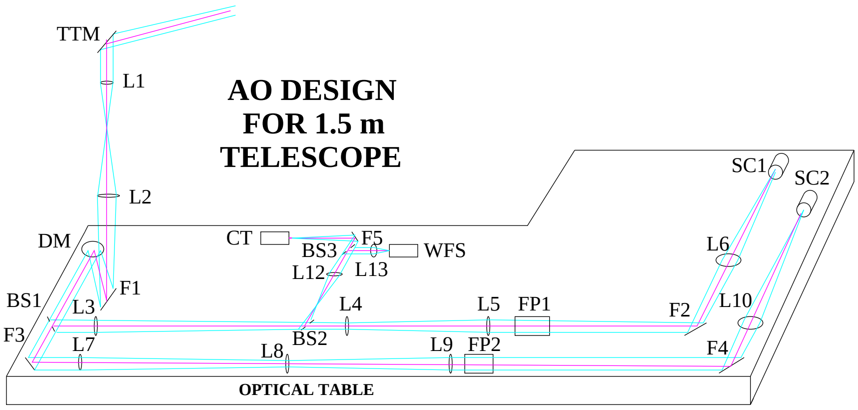

Figure 5: The optical layout of the BBSO adaptive optics system for the 63-inch telescope (not to scale). TTM guides the light from the telescope to the optics laboratory on the floor beneath. “DM”, “F”, “BS”, “CT”, “WFS”, “PFI” and “SC” mean deformable mirror, folding mirror, beam splitter, correlation tracker, wavefront sensor and science cameras, respectively.

about 0.2″/pixel may work simultaneously with a signal-to-noise ratio of about 400 and 600 for a 0.25 sec integration time. This performance is nominal and quite satisfactory for our needs. Thus, the adaptive optics system will feed the downstream scientific instrumentation.

D Instrumentation

There are several on-going instrumentation projects at BBSO. Here, we discuss the ones that will benefit the most from the adaptive optics, while making optimal use of the larger aperture of the 63-inch telescope.

D.1 Visible Light Vector Magnetographs

Our project to make a new Digital Vector MagnetoGraph (DVMG) system is completed. (Spirock et al., 2001). The DVMG uses a 1K×1K pixel CCD camera (12 bit, 15-30 frames/s) manufactured by Silicon Mountain Design/Dalsa, and has no moving parts. The DVMG has markedly increased the sensitivity and accuracy of our magnetograms – representing a significant improvement over the old, supplanted videomagnetograph. The operational DVMG system serves as the basic model for the first of our two new Fabry-Pérot filter-based magnetograph systems, which will yield absolutely calibrated vector magnetograms. The approach here reflects our approach to instrumentation in general – each new system builds on its predecessor. The DVMG was built on an earlier version that could not measure vector fields. The Visible light Imaging vector Magnetograph (VIM) – which will use a Fabry-Pérot etalon – will utilize the DVMG experience. The DVMG is part of the Ph.D. thesis work of Tom Spirock, who has been supported by AFOSR. With the VIM, we will be able to make much more accurate and higher resolution measurements of the evolving magnetic fields in flare-producing active regions. The DVMG will stay on the 25 cm telescope, which will be installed as a turret on the “nose” of the dome. This will allow us to make lower resolution observations of larger fields of view (so we can simultaneously see the large- and small-scale manifestations of the phenomena under study). The VIM will reside on the optical bench, as indicated in Figure 5 by FP1 and FP2, while its polarizing optics will lie on the 63-inch telescope to minimize polarization problems arising from the downstream mirrors. The VIM will use its Fabry-Pérot filter to provide the spectral line profile and the full Stokes vector when observing photospheric magnetic fields. This improvement will preclude Zeeman saturation where the fields are strong (in sunspots), and it will also provide filling factors for weaker fields. The VIM is designed to operate at the diffraction limit of the 63-inch telescope covering a substantial field of view (FOV) of about 170″. In addition, by selecting an appropriate interference filter, any spectral line in the range from 5500 Å to 7000 Å can be studied, e. g., Fe I 630.15 nm and 630.25 nm, Ca I 610.3 nm and 612.2 nm, Hα, Na D_1 and Na D_2, and non-Zeeman lines Fe I 557.6 nm and 569.1 nm. The high transmission of the system (no Lyot filter) will also allow real-time image reconstruction (see Section D.3) of narrow band ($\sim$100 mÅ) filtergrams so that we can study, for example, the Hα fine structure with high spectral, temporal and spatial resolution. With the DVMG and VIM, we will be able to measure the magnetic field at two altitudes to determine the field's height variation. We have all the necessary hardware in hand, and expect to complete the VIM within a year.

D.2 Infrared Vector Magnetograph

We have installed an infrared (IR), spectrograph-based magnetograph system at BBSO. For this, we purchased an In Ga As camera (320×240 pixels, 12 bit, 60 frames/s) – a camera in which NJIT played an important developmental role. The camera is optimized between 0.9 and 1.7 μm, and has a quantum efficiency better than 70% over that range. We also developed the necessary optical, electrical and computer software components for the system. The next significant part of our IR instrumentation was the development of a narrow bandpass filter system, which combines a Lyot filter and an IR Fabry-Pérot filter – the Infra-Red Imaging vector Magnetograph (IRIM) with support by DURIP funding. A recent NJIT Ph.D. graduate, Jingshan Wang completed the Lyot filter. We have our operational IR Fabry-Pérot in hand with the same DURIP support. Our one-of-a-kind Lyot filter has a bandpass of 0.25 nm at 1.56 μm, giving us a 0.25 nm wide prefilter (narrower than the 0.5 nm free spectral range of the IR Fabry-Pérot). This will solve the longstanding problem of constructing a filter-based IR magnetograph, while avoiding the complications of using a double etalon system. At this time, regularly operating, stable dual etalon IR systems do not exist. With our system, polarimetry in the near IR will have the same reliability and stability as it now has for visible light. Note that the IR Lyot filter system has about 20% transmission. IRIM's total transmission is about a factor of two less than that of a dual Fabry-Pérot instrument. However, unlike a dual Fabry-Pérot system, with its quite restricted FOV, our system can utilize almost the entire FOV of the 63-inch telescope (180″). In addition, a new detector technology (CMOS devices) offers high quantum efficiency, so we will be able to take individual exposures well within the correlation time in the near IR ($\sim$ 100 ms). The strength of the IRIM is its extreme sensitivity and high spatial resolution (0.6″), which allows us to study weak and small-scale magnetic fields in the quiet sun. The sensitivity goal is in the order of 0.1 mT for the line-of-sight component and 5 mT for the transverse component of the magnetic field.

We expect the first generation of the IRIM to be on-line shortly after the VIM. We are presently obtaining, under DURIP support, a large format IR CMOS camera ($\sim$1K×1K) pixel from Rockwell Scientific Imaging.

The VIM and IRIM will be able to operate simultaneously, which means we can obtain high resolution observations of the sun's structure at different altitudes in the solar atmosphere. The VIM and the subsequent IRIM (FP2 and SC2 in Figure 5) systems will be located in the Coudé Room one floor beneath the telescope, but like the VIM the polarization optics will reside on the 63-inch telescope. We expect the IRIM to be ready a year after the VIM. The optical design for this project is coordinated with the one for the adaptive optics project and the 63-inch telescope. VIM, IRIM, and the real-time image reconstruction system have all been designed for diffraction limited observations, i. e., the photon flux per diffraction limited resolution element is constant. Therefore, only the transfer optics have to be modified to accommodate a larger aperture telescope.

D.3 Real–Time Image Reconstruction

In recent years, post-facto image processing algorithms have been developed to achieve diffraction limited observations of the solar surface. We are about to use the speckle masking imaging technique, in combination with a parallel computer built of 32 1.8 GHz AMD Athlon processors, to yield near real-time time-series with a cadence of approximately 1 min, which is sufficient to resolve the evolution of solar surface phenomena, such as granulation, pores, sunspots and including the fine-structure of sunspot umbrae and penumbrae. We emphasize that there is no such system in existence at any observatory. Our first observations are scheduled during the 2002 observing season. Without the parallel computer, the processing time for each data set ranges between one–half to 16 hours, depending on image size and truncation of the speckle masking bi–spectrum. This effectively limits us to a short observing day (~ 2 hours) because the controlling computer's disk is filled by storing all the raw data, so the chances are slim of obtaining a sequence containing the long term evolution of an active region, and catching flares during the observations. Further, we will not know if we have been lucky until the next day.

The power of parallel computing has not yet been exploited in solar physics. Supercomputers have been used for numerical calculations in astrophysics, however they cannot be used for real-time data processing because the observational data cannot be transferred to the supercomputer centers in real-time. Usually, only a few data sets are analyzed per year, and only at the end of this process does one discover whether something really interesting has been captured. This is due to the long computation time, so raw images have to be saved to be processed off-line, and a hard disk is filled up very quickly. The time-lag between the observation and the data analysis is far too long for any sort of rapid response, such as would be needed for space weather warnings and flare forecasting. Furthermore, the time lag renders the whole scientific enterprise less efficient than it needs to be, considering today's computer technology.

We have a 4–node system and have developed and tested the needed software for the 32–node system (Denker et al., 2001). Speckle masking imaging requires a sequence of short–exposure images (less than 10 ms) to "freeze" the wavefront aberrations, which makes it possible to separate the object information from the information on atmospheric turbulence. The first steps in preprocessing the data concern the usual corrections by means of the average dark and flat field image. The image displacement within the sequence is removed with respect to the image with the highest rms-contrast. In the near future, this step in the data reduction will be replaced by a correlation tracker, which compensates image motion at a rate of up to 2000 Hz. Since speckle interferometry is only valid for a small region, the isoplanatic patch, the specklegrams have to be divided into mosaics of partially overlapping sub-images. Each isoplanatic patch has a size of approximately $6'' \times 6''$. This presents an ideal problem for parallel processing, since each processor is assigned its own sub-image to reconstruct. We have successfully tested the whole system by taking real observational data, and reconstructing diffraction limited images in real–time. The new 32 CPU system will reconstruct a $100'' \times 100''$ FOV. Diffraction limited images will be obtained at a one minute cadence.

We note that when our adaptive optics system is in place, it will aid the reconstruction and provide a powerful test of it, but it will not replace the need for speckle reconstruction, because the adaptive optics system fully corrects on a single isoplanatic patch (of order a few arc seconds in extent at 500 nm) with decreasing correction for more distant patches. Only multi-conjugate adaptive optics would fully correct the entire field of view. There is no such system in existence at this time. Our new parallel computing system will only save reconstructed image data, and therefore, the disk will be big enough for several days of continuous observation.

Parallel processing of solar data will literally provide a new window through which we can observe the sun in exquisite detail, and study the evolution of granulation, sunspots, prominences, and flares. For highly dynamical features, such as flares, the parallel processing will be useful in determining, say, the evolution of the photospheric structures that trigger the dynamic phenomena. For parallel processing, the underlying data processing algorithms are understood, but the complexity is such that only parallel computing enables us to visualize and interpret large data sets effectively.

E Unique Science and Support for Space Missions

E.1 High Resolution, High Cadence Studies of Solar Flares

With observations of unparalleled resolution from BBSO's 63-inch telescope, we will make significant progress, which would otherwise be beyond our reach, in our on-going efforts to understand solar flares.

High cadence X-ray and microwave observations have revealed a temporal fine structure (sub-second) in solar flares, called elementary flare bursts (see the review paper by Sturrock, 1989). These may be attributed to the fine structure in coronal magnetic fields, which are related to the aggregation of photospheric magnetic fields into "magnetic knots". Very recently, the BBSO group has experimented with high cadence flare observations (Wang et al., 2000, Qiu et al., 2000, 2001, 2002), probing the far blue wing of Hα with a cadence between 10 ms to 33 ms and an image scale of $0.5''$. In particular, Wang et al. (2000) found the Hα source of sub-second hard X-ray bursts. Qiu et al. (2002) studied the footpoint shifts of flare kernels and derived the DC electric current as a function of time. This current was found to be coincident with the hard X-ray temporal profile, and therefore, clearly revealed the flare acceleration mechanism.

The 63-inch telescope can obtain high resolution, high cadence images of flares in wavelengths such as He D_3 and off-band Hα. These observations will provide details of electron precipitation on fine temporal and spatial scales. By combining high cadence optical imaging with hard X-ray imaging from missions (such as a future mission replacing the Ramaty High Energy Solar Sprectroscopic Imager (RHESSI)), as well as with high resolution magnetograms, we expect to learn if and how, the individual sub-second peaks in the hard X-ray and microwave time profiles correspond with the rapid precipitation along various flux loops. Since the 63-inch telescope will provide a spatial resolution of ≈ 50 km in the visible wavelength region, we will be able to determine whether the moving flare kernels have such a small scale. At this moment, our resolution is only about 300 km under excellent seeing conditions and without image correction. Including adaptive optics on our current 26-inch telescope, we anticipate 150 km resolution under most observing conditions. With the 63-inch telescope, under better than average seeing conditions, we anticipate 50 km resolution. The 50 km scale is important, since many models predict this value for the cross section of fluxtubes, see Schüssler (2001).

E.2 Structure and Evolution of Magnetic Fields in Flaring Active Regions

We plan to use the 63-inch telescope to answer the following questions: (a) What is the role of the evolution of the photospheric magnetic field in triggering solar flares, and what is the relationship between the magnetic configuration and the properties of flares? (b) How do electric currents evolve, and what is their relationship to particle precipitation?

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. So, the study of magnetic fields is a very important component of flare science. This concept of energy release has motivated many attempts to detect flare-induced changes in the magnetic fields of active regions.

So far, we have failed to detect, in any consistent way, the changes in magnetic fields associated with solar flares. The inconsistency of the results is due to observational limitations. We cannot get high temporal and spatial resolution, as well as high polarization accuracy at the same time, with existing telescopes/instruments. Our new, large telescope will provide much more reliable and high quality measurements of vector magnetic fields. A lot of the ambiguities discussed above will be resolved with the new higher resolution, higher cadence data. In addition to the temporal and spatial resolution mentioned earlier, the precision of the polarimetry would be on the order of 10^{-4}. With the improved accuracy of our vector magnetograph system, studies of more examples of evolving magnetic fields, and active regions, and changes due to flares will provide the evidence needed to lead us to understanding the process of flare energy release, and the role of photospheric magnetic fields therein.

It is well known that emerging flux regions (EFRs) are closely associated with solar flares and the onset of CMEs (e.g., Feynman and Martin, 1995). This is not difficult to understand, as new flux emergence may perturb the magnetic configuration above the solar surface. It has also been found that complicated flow

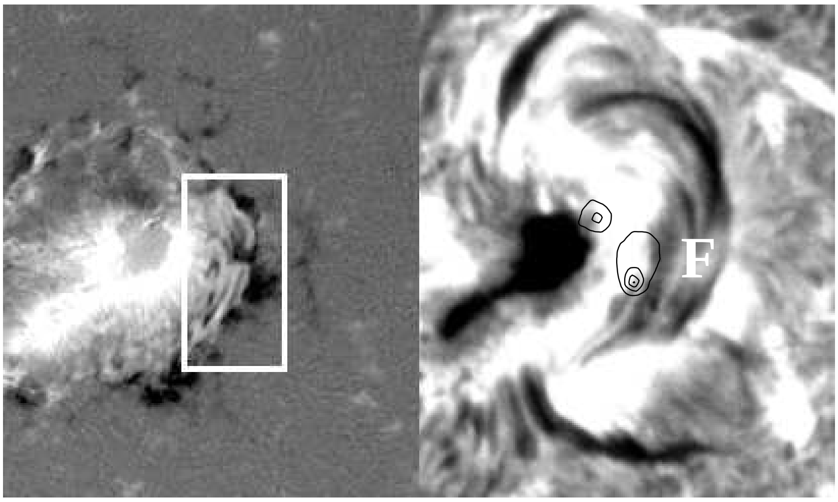

Figure 6: Left: a line-of-sight DVMG image of November 24, 2000. The white rectangle encloses a magnetic channel structure (characterized by the striations). The field-of-view is $150'' \times 180''$. Right: Hα image of the X2 flare at 21:53 UT, in the same field of view as the magnetogram. An erupting flux rope is denoted by F, and the black contours show Yohkoh hard X-ray kernels.

patterns on the solar surface may actually be due to flux emergence of twisted fluxtubes (Tanaka, 1991). Zirin and Wang (1993) discovered another kind of flux emergence – flux emergence inside the penumbrae of existing sunspots. This kind of new flux emergence can produce so-called magnetic channel structure: elongated magnetic striations, which have alternating magnetic polarities and strong transverse magnetic fields along the channels. Flows are observed along the channels, as well. It is also known that this is the common property of a few super-active regions, which produced multiple major solar flares, such as NOAA 5395 in March 1989, NOAA 6659 in June 1991, and NOAA 9393 in March/April 2001. The channel structures only appear in the best quality magnetograms. Figure 6 shows one of the best magnetograms we obtained with one of our present telescopes. The resolution is about 500 km. The 63-inch telescope will be able to reveal the physics of these channel structures, and the reason why they are so closely associated with major solar flares, as we can detect the structures with at least three times finer resolution.

E.3 Dynamics of Kilogauss Flux Tubes

One of the major breakthroughs in solar physics during the last 40 years has been the discovery that most photospheric magnetic flux that is measurable in visible light, via Zeeman polarization, appears outside of sunspots in the form of small scale flux concentrations with field strengths of typically 1 to 2 kG. Evolving from this discovery is the picture of small fluxtubes with typical sizes of a few tens to a few 100 kilometers, as building blocks of plage and network magnetic fields. Sophisticated Magneto-HydroDynamic (MHD) models now offer a variety of predictions that need to be tested. Also, precise measurements are necessary in order to define boundary conditions for these models.

The main questions about the dynamic behavior and structure of small scale kilo-Gauss fluxtubes, which need to be addressed with the 63-inch telescope, concern the formation of photospheric flux concentrations with field strength above the equipartition field strength, and the dynamic interaction with the turbulent photospheric atmosphere. The observational verification of the process(es) that leads to kilo-Gauss flux concentration in the solar photosphere, where the equipartition field strength is only about 500 G, is a fundamental problem in solar and stellar physics that needs to be solved, and better than 100 km resolution is critical to resolve this problem.

Understanding the dynamic interaction of photospheric flux concentrations with turbulent granulation is essential in order to estimate the total energy flux that is transmitted/channelled by small-scale fluxtubes into the higher atmosphere.

Here we list basic science questions that can only be addressed with a 63-inch telescope (as opposed to our current 26-inch telescope):

- How are fluxtubes formed and how do they evolve?
- What is the lifetime of a fluxtube?
- How do the fluxtubes interact with turbulent flows in the photosphere?

E.4 Magneto-Convection in Sunspots

With the appreciably higher resolution of our new telescope, combined with powerful tools in visible and IR imaging, we will make substantial progress in answering the following questions:

- Origin and dynamics of umbral dots: oscillatory convection vs. field free plumes.
- Oscillatory convection: test model predictions.
- Sub-photospheric structure of sunspots – 3-D structure of sunspots.
- Origin and dynamics of umbral and penumbral oscillations.
- Origin and dynamics of penumbral fine structure.
- What is the size distribution of penumbral filaments?
- MHD waves in sunspots: test model predictions.
- Are there oscillations in the umbral magnetic field strength?

E.5 Heating of Upper Atmosphere

Recently, there have been some significant advances in the research on the origin of coronal heating. Our new telescope will provide breakthroughs in this area for two reasons:

(1) We will provide direct measurements of magnetic reconnection rates in the quiet sun. Figure 7 is the most sensitive magnetogram that we can get now with our current telescope. We can obtain 3 times better resolution or 10 times better sensitivity (or a compromised setup between these two) with the 63-inch telescope. By keeping the same pixel resolution we have now, but using the 63-inch telescope as a light bucket, we can obtain a sensitivity of about 0.1 G for the line-of-site component of the magnetic field. Alternatively, if we go for maximal spatial resolution – assuming a nominal circular FOV of $180''$ and an image scale of $0.17''$ pixel^{-1}, we estimate that IRIM's sensitivity is 1 G for the line-of-sight component and 5 G for the transverse component of the magnetic field. Either way, we will be able to detect a lot more intra-network fields and their interaction with network fields. Therefore, we will be able to accurately measure the energy released during the reconnection of these fields.

(2) Parker (1988) proposed that the X-ray corona is due to a continuous nanoflaring process. The energy source of these nanoflares is from the random motion of footpoints. So the observations of footpoint motions associated with all the above events is essential. We know that such footpoint motion is hard to observe and characterize in lower resolution observations with the current system. We plan to detect and characterize such footpoint motions with $0.1''$ spatial resolution, using real-time speckle constructed images. As G-band images show fluxtubes very well, we will use our G-band filter to observe for this part of the research. We expect to learn the correlation between footpoint motions and brightness of overlying EUV/X-ray loops.

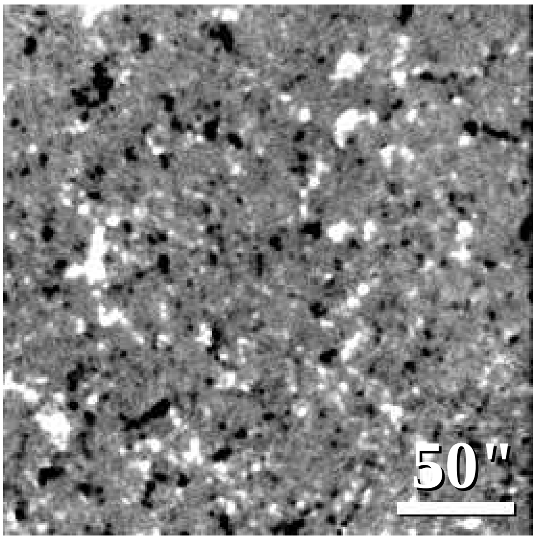

Figure 7: An example of a longitudinal magnetogram using the DVMG, in which the bright and dark represent the opposite magnetic polarities. The FOV is $235'' \times 235''$ and the cadence is 1 min. The intranetwork fields are clearly apparent everywhere. Unlike an old videomagnetogram, the images here are flat-fielded and calibrated. The flux density sensitivity is about 1 G. The new telescope should give us a sensitivity of about 1 G, but with a spatial resolution that is about 2-4 times better.

E.6 Earthshine

By looking at the dark side of the moon, one can obtain a large scale measure of the earth's reflectance (Goode et al., 2001). Further, the earthshine spectra carry detailed information about the global properties of earth's atmosphere. We would like to know how the atmosphere's composition and temperature change with the seasons, and if there are long term changes. Earthshine has travelled through the atmosphere three times (twice globally and once locally), during which molecular absorption spectra are formed. The local absorption and solar spectrum can be removed by dividing the earthshine spectrum by the moonshine spectrum. A careful study of the earthshine spectrum yielding an accurate measurement of the molecular parameters can help to determine global atmospheric quantities, like temperature, water vapor content, cloud optical depth and pressure. We have been making our measurements using the 63-inch telescope on Mt. Palomar. But with this telescope, there is no detector in the IR, where many of the strongest greenhouse gas lines reside. With our 63-inch telescope, we can detect bandwidths, including the IR, that will enable us to determine populations, and their changes. Thus, we plan to use the 63-inch telescope at night to monitor the earth's climate. We will use a fibre-optics spectrograph getting light from the IR bench mounted to the telescope, which draws its light through the hole in the primary (see Figure 3).

E.7 Support of Space Missions

The 63-inch telescope will complement, and provide support and context observations for planned space missions such as SOLAR-B (launch 2006), Solar Dynamics Observatory (SDO) (launch date 2007), and STEREO (launch date 2006). Among all the current and future missions, only Solar-B will provide high resolution observations. However, the aperture of Solar-B is only 50 cm. It's diffraction limit is only one-third that of our proposed telescope. Our IR capability is also unique.

For the STEREO mission, the major objective is to provide a 3-D view of CMEs. Our observations will provide valuable magnetograms and images to understand the magnetic evolution of CMEs.

SDO will provide large scale, lower resolution magnetic field observations. Our new telescope will provide complementary high resolution observations.

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G Personnel and Vitae

Professors Goode, Wang and Denker are from Big Bear Solar Observatory of New Jersey Institute of Technology. The three will work closely together, with Professor Goode as the PI, having overall responsibility for the project.

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Ten Selected Recent Publications

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"Inter-Active Region Connection of Sympathetic Flaring on 2000 February 17, 2001", Wang, H., Yurchyshyn, V., Chae, J., Yang, G., Steinegger, M., and Goode, P. R., ApJ, 559, 1171

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