DOI 10.1007/978-1-4899-8005-2_20
Reprinted from *Solar Physics* Journal, DOI 10.1007/s11207-013-0235-6

Infrared Observations from the *New Solar Telescope* at Big Bear

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Received: 20 February 2012 / Accepted: 21 January 2013 / Published online: 21 February 2013

Abstract The 1.6 m clear aperture solar telescope in Big Bear is operational and with its adaptive optics (AO) system it provides diffraction limited solar imaging and polarimetry in the near-infrared (NIR). While the AO system is being upgraded to provide diffraction limited imaging at bluer wavelengths, the instrumentation and observations are concentrated in the NIR. The *New Solar Telescope* (NST) operates in campaigns, making it the ideal ground-based telescope to provide complementary/supplementary data to SDO and *Hinode*. The NST makes photometric observations in Hα (656.3 nm) and TiO (705.6 nm) among other lines. As well, the NST collects vector magnetograms in the 1565 nm lines and is beginning such observations in 1083.0 nm. Here we discuss the relevant NST instruments, including AO, and present some results that are germane to NASA solar missions.

Keywords Observational near infrared astronomy

1. Overview

The 1.6 m clear aperture solar telescope ("NST" or *New Solar Telescope*) in Big Bear Solar Observatory had its first light in January 2009 with first science grade data in the Summer of 2009 and first data corrected by adaptive optics (AO) in the Summer of 2010. The NST is the first facility-class solar telescope built in the US in a generation. As shown in Figure 1, the NST is a modern, off-axis 1.6 m clear aperture instrument (Goode *et al.*, 2010; Cao *et al.*, 2010; http://www.bbso.njit.edu/nst_project.html) that offers a significant improvement in ground-based, high angular resolution and polarimetric capabilities. Early observations have been concentrated in the near infrared (NIR) because of limitations in AO, which

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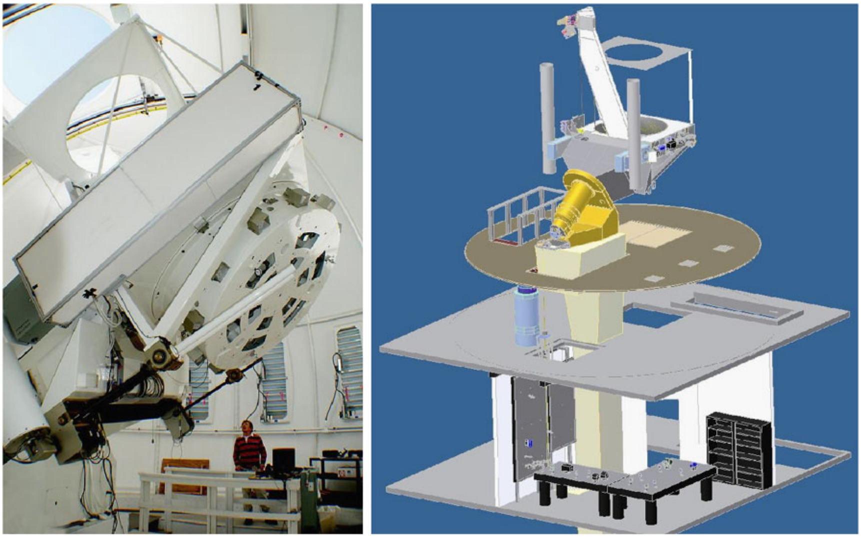

Figure 1 Left picture shows the 1.6 m off-axis NST with the primary mirror cell shown in the foreground. The design was driven by competing needs for rigidity atop the secondary mirror tower and an un-obscured light path throughout the telescope. Right schematic shows the full optical path through the NST with the bottom floor housing all instruments that are fed light from the AO.

Table 1 Milestones in NST commissioning.

Date	NST Milestone	Observations Enabled
January 2009	First Light with NST	Visible Light Photometry ($0''.50$)
Summer 2009	First Diffraction Limited Observations	Visible Light Photometry ($0''.12$)
Summer 2010	AO Corrected Observations	Visible & NIR Photometry ($0''.10$ – $0''.20$)
Summer 2010	AO Corrected Magnetograms	NIR Vector **B** ($0''.40$)
Fall 2012	AO-308 Observations	Photometry in Bluest Light ($0''.05$)
Spring 2013	IRIM Upgrade to Dual FPI System	Higher Cadence Vector **B** in NIR ($0''.20$)
Spring 2013	VIM Installation	High Spatial Resolution Vector **B** ($0''.10$)
Summer 2013	First Observations with MCAO	AO Correction over Full $70'' \times 70''$ FOV
Fall 2013	CYRA First Light	Spectroscopy Covering 1.0 – 5.0 μm

are now being solved by larger format deformable mirrors (DMs), as will be discussed. Key milestones of NST commissioning are listed in Table 1. The telescope is well into its commissioning phase.

The telescope 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). The working wavelength range covers 0.4 to 1.7 μm in the Coudé Laboratory two floors 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

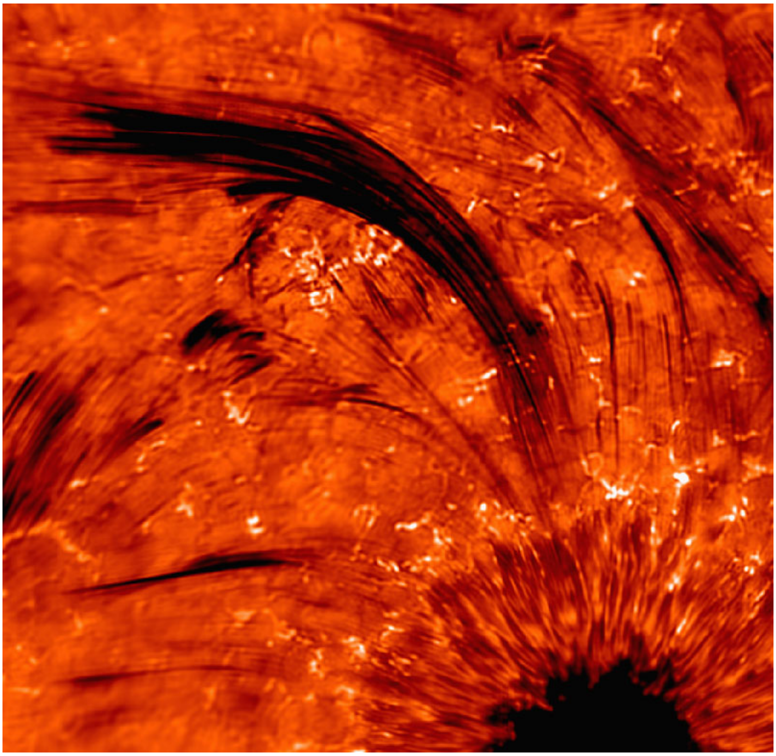

Figure 2 Off-band Hα −0.75 Å image taken on 2 July 2010 revealing the dynamical layer overlying the surface region above a sunspot. Most apparent are the long dark streaks, so-called "jets" arising from the bright magnetic regions on the edge of the penumbra.

light is fed to the Coudé Laboratory. An off-axis design was chosen principally because of its vastly reduced stray light, since there is no central obscuration to degrade the telescope's MTF (modulation transfer function) at high spatial frequencies.

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

The NST has a fully operational, nearly achromatic adaptive optics (AO) system on a vertical bench in the Coudé Laboratory for diffraction limited imaging, as illustrated in Figure 2. The Hα image in Figure 2 reveals the dynamical layer overlying the surface region. Most apparent are the long dark streaks, so-called "jets" arising from the bright magnetic regions on the edge of the penumbra. The image benefited from adaptive optics, which enabled real-time correction for atmospheric distortion. 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 National Solar Observatory (NSO). NST images also routinely undergo post-facto reconstruction. The Kiepenheuer-Institut für Sonnenphysik's software package for speckle interferometry of AO corrected solar data (KISIP) is a post-AO reconstruction algorithm allowing one to achieve the diffraction limit of the telescope over a larger field of view than the isoplanatic patch for most observations (Wöger, von der Lühe, and Reardon, 2008).

The AO-76 system tracks on granulation for the NST, while with the old 0.6 m telescope we were 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. The success of AO-76 on the NST was no surprise, rather it was foreseen in a detailed and realistic error budget analysis (Rimmele, 2008, private communication) that included AO residuals, telescope and instrument error budgets, and the steady, good BBSO seeing (an AO correctable $r_0 \sim 9$ cm at 550 nm all day long during the summer observing season, which is easily sufficient for AO-76 to lock on granulation). This Fried parameter is in the mid-visible wavelength range and was determined from measurements of the atmospheric turbulence ("C_n^2") as a function of altitude above BBSO (Kellerer *et al.*, 2012). These are the first such measurements at a US solar observatory. The Fried parameter, r_0, is the coherence length of the atmospheric turbulence. For telescope apertures larger than r_0, resolution is seeing limited. In the summers of 2010 and 2011, AO was able to lock on granulation for extended periods of time. In the winter, attaining AO lock for extended periods was more problematic because of generally poorer seeing than in summer. 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 error budget analysis of Rimmele (2008, private communication) using the more pessimistic annual average $r_0 \sim 6$ cm (the 9 cm value comes primarily from summertime when the seeing is much better) from the ATST site survey (http://atst.nso.edu/site) in Big Bear showed that AO-76 will yield, in the detector plane, a high Strehl of about 0.7 in the near infrared (1 μm) under median, annualized BBSO seeing conditions. However, in the visible (0.5 μm), AO-76 will deliver a sufficient Strehl (~ 0.3, which would imply diffraction limited imaging of the solar disk) only under well-above average summer seeing conditions. However, most of the time the Strehl would be more like $\sim$0.1. Thus, in visible light our observations using AO-76 are better at the red end of the visible spectrum. The low Strehl matters especially for polarimetric observations, which 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. Thus, truly diffraction limited observations, especially of the magnetic field will be rare in the visible spectrum, even though they would be critical for the highest possible spatial resolution.

Basically, to make AO corrections, at least one subaperture of the wavefront sensor (WFS) is required for every resolution element of atmospheric wavefront distortion. Roughly, if $r_0 \sim 10$ cm a 60 cm aperture telescope needs a WFS with $6 \times 6 = 36$ (36 subapertures) and the 97 actuator DM of AO-76 is more than sufficient for diffraction limited observations with a superb optical telescope. However, for the 1.6 m NST, $16 \times 16 = 256$ subapertures would be required. However, r_0 scales as $\lambda^{\frac{6}{5}}$, which corresponds to 20 cm in the NIR at 1 μm under the reasonable and standard assumption of Kolmogorov turbulence. In this case, the minimum WFS format would be $8 \times 8 = 64$, so AO-76 if fine. For Hα, AO-76 is inadequate, which means polarimetry in visible light is not possible except under extraordinary seeing conditions. However, imaging with speckle reconstruction can yield good images, like Figure 2. But G-band imaging would require a higher order AO system even for imaging. Thus, so far NST usage has been concentrated on the NIR. For these reasons, we have been working on a higher order AO system.

We have been developing, in collaboration with NSO, an AO system based on a commercially available 357 actuator DM (AO-308), which, based on the same kind of error budget analysis, we realistically expect to achieve a Strehl of 0.3 in the detector plane in the visible (0.5 μm) even for median, annualized BBSO seeing conditions (Rimmele, 2008, private communication).

The AO-308 project is well under way. We have purchased two 357 actuator DMs from Xinetics. Each has a special faceplate made of silicon instead of ULE (ultra-low expansion glass) 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 wavefront sensing camera (Phantom V7.3 from Vision Research). Each hardware element and its connections to its partners has been successfully tested. What remains is DSP control and the graphical user interface, with the former being built on the programming from AO-76. The optical design of AO-308 is close to that of AO-76 requiring only the replacement of two optical elements in the AO-76 feed. The AO-308 system is undergoing its commissioning phase as of this publishing and have full operation shortly thereafter.

With AO-308 feeding light to our optical instruments in the Coudé Laboratory, BBSO will collect a richer spectrum of data. The next, and on-going AO project is Multi-Conjugate Adaptive Optics (MCAO), which will follow shortly thereafter. In collaboration with NSO and with *Advanced Technology Solar Telescope* (ATST) in mind, we are developing a MCAO system for the NST that will expand the effective isoplanatic patch of diffraction limited observations in the field of view (FOV) by nearly an order of magnitude to at least 70″. The expansion of the diffraction limited FOV will be sufficient to cover entire active regions enabling photometric, spectroscopic and polarimetric observations, which include, for instance, flares that might 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 the requisite high temporal cadence and with the NST's unprecedented spatial resolution, fundamental scientific questions like the onset and evolution of flares, flare triggering mechanisms, magnetic reconnection events and many other dynamic solar phenomena, which would be best performed with diffraction limited observations over an extended FOV. Such data will provide an excellent supplement/complement to SDO and *Hinode* data. Of course, for slow (about 5 s) cadence observations, the NST will use AO-76, then AO-308 combined with speckle reconstruction, while for appreciably higher cadence we will suffer some from the gradual roll-off in resolution as we move further from the isoplanatic patch. Of course, the NST is a 2 m^2 "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.

2. NIR Photometry and Polarimetry

The IRIM (*InfraRed Imaging vector Magnetograph*) system developed by BBSO is in operation (Cao *et al.*, 2011) on the NST using light fed from AO-76. We show the Q, U, and V components of a vector magnetogram in Figure 3. We note that severe polarization problems precluded obtaining vector magnetograms from the old, 0.6 m BBSO telescope and that BBSO vector magnetograms from that era were from a 20 cm aperture telescope. The superior optical design of the NST and good polarization calibration have already enabled us to obtain vector magnetograms with minimal cross-talk, as is clear from Figure 3 where

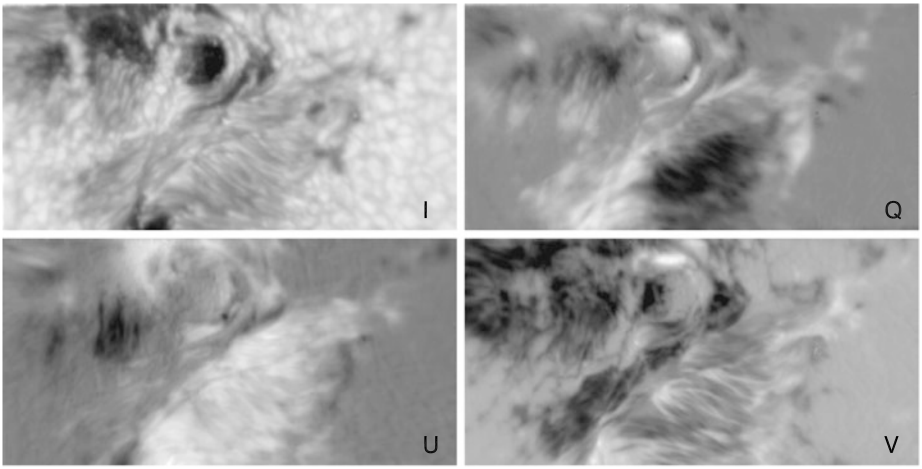

Figure 3 Calibrated IRIM vector magnetogram without any image reconstruction near AR 11283 at 463″W 119″E, taken on 7 September 2011. Stokes I and V are sliced in the blue wing of the Fe I 1564.85 nm line while Q and U are sliced in line center. Dual-beam technology was employed to minimize seeing-induced noise. The field of view of IRIM is about 50″ × 25″.

there is no apparent cross-talk of the line-of-sight component within the two transverse components.

The NST magnetograms in Figure 3 are from IRIM, which 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. The temporal cadence for the IRIM vector magnetograms is 30 s, but it will be about five times faster when its Lyot filter is replaced by a second Fabry-Pérot Interferometer (FPI) in the Spring of 2012, so the second generation IRIM will be available shortly thereafter. IRIM's first imaging polarimetric observations at 1565 nm were made at the diffraction limit on 1 July 2005 using BBSO's retired 0.6 m telescope (Cao *et al.*, 2006). Stokes-V profiles were obtained from the FPI scan, 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 the observations (ignoring the factor of eight difference in aperture of the NST and that of the old BBSO magnetograph). But this is not true, after all, Zeeman splitting increases quadratically with wavelength, so IRIM can more precisely detect magnetic flux. Thus, 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). Additionally, the terrestrial atmosphere is more benign in the NIR with the mean, annualized Fried parameter at BBSO being about 25 cm (under the standard assumption of Kolmogorov 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 focal plane Strehl in the NIR is sufficient to enable sustained diffraction limited images with AO-76 under typical BBSO observing conditions. 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

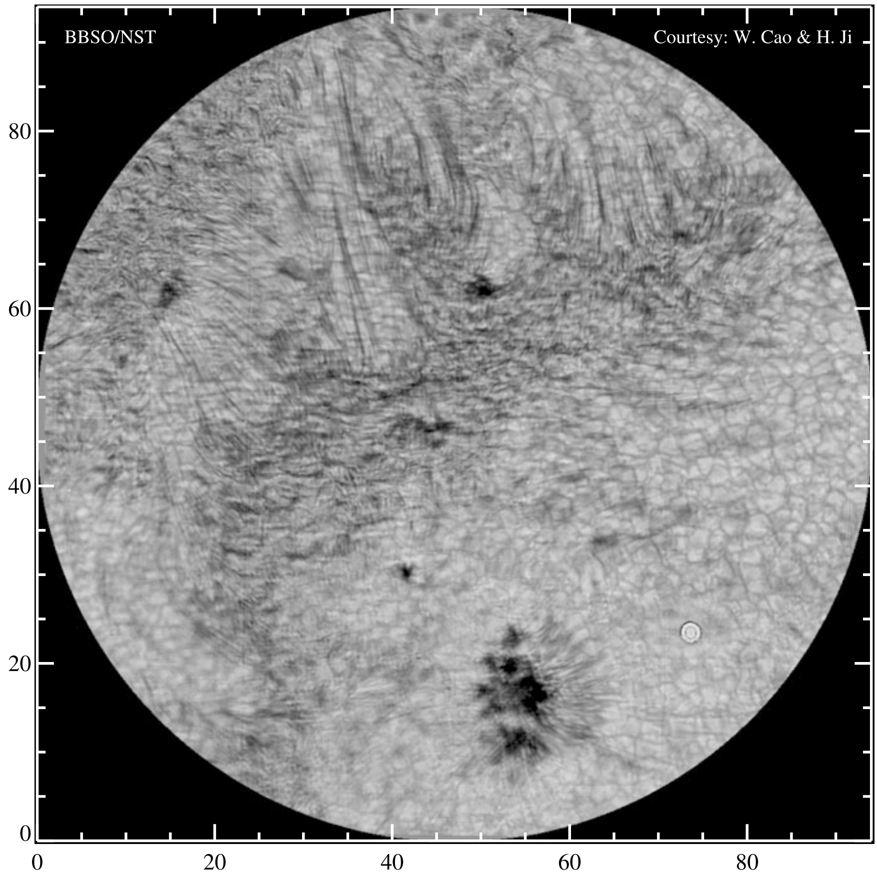

Figure 4 He I 10830 Å image take with IRIM on 22 July 2011 revealing a previously unknown, hyperfine magnetic loop structure in active region NOAA 11259. In this example, the loops primarily connect areas of opposite polarity. The field of view is 94″ × 94″.

be our nominal 10^{-3}. The spatial resolution will be around 0″.2 for direct imaging, and 0″.4 for magnetograms.

We are upgrading IRIM to a dual FPI system (replace Lyot filter with second FPI), so that we can fine tune to any wavelength between 1.0 and 1.7 µm, rather than being confined by the Lyot filter to the 1.6 µm regime with IRIM. The upgraded instrument is called NIRIS (NIR *Imaging Spectropolarimeter*). NIRIS (Cao *et al.*, 2012) will have all the capabilities of IRIM with five times the cadence. It has a broader wavelength coverage over the NIR that will enable NIRIS to measure the magnetic field in the upper chromosphere and base of the corona using the He I 10830 Å line. Such measurements have only been made with spectrographs, like SOLIS until now. NIRIS will be on-line in the Spring of 2013 (see Table 1).

With IRIM, we occasionally substitute a 0.5 Å narrow bandpass Lyot filter centered on 10830 Å. With this, we have obtained images like that in Figure 4 in which one can see a hyperfine system of magnetic loops reaching up to the base of the corona. The loops have a typical cross-section of about 100 km, which is about the same as the diffraction limit of the NST at 1 µm. The He I 10830 Å line is formed in the upper chromosphere and transition region. A striking feature is that the thickness of the loops remains almost constant over long distances. We have also attained preliminary magnetograms from IRIM with the 10830 Å Lyot filter. With NIRIS, we will have about five times more light and a tighter bandpass.

The weakness of IRIM is the spatial resolution, but this problem will be solved using our *Visible Imaging Magnetograph* (VIM). VIM was in use on the old BBSO telescope and obtained spectroscopic data and line-of-sight 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 fully diffraction limited operation of VIM will require AO-308, we chose to bring IRIM on line first. For the work described here, we will have AO-308 and VIM for science that requires vector magnetograms of the highest spatial resolution ($0''.1$).

2.1. Mid-IR Spectroscopy

The *CrYogenic infRAred Spectrograph* (CYRA) spanning 1.0 to 5.0 μm will help the NST achieve its scientific potential of a new and improved probing of 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 (Pierce, 1964; Penn *et al.*, 1991) – one operating at the National Solar Observatory (on the McMath-Pierce telescope) and the other at the 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, whereas CYRA will be fully cryogenic. 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 and into the corona, as well as observations of dimmer targets such as sunspot umbrae and off-limb features.

Acknowledgements We thank BBSO observing staff and instrument team for their support. W. Cao and P.R. Goode acknowledge the support of the US NSF (AGS-0847126 and AGS-0745744), NASA (NNX08BA22G), and AFOSR (FA2386-12-1-3018 and FA9550-09-1-0655).

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