A new multi-wavelength solar telescope: Optical and Near-infrared Solar Eruption Tracer (ONSET) *

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Abstract  A new multi-wavelength solar telescope, the Optical and Near-infrared Solar Eruption Tracer (ONSET) of Nanjing University, has been constructed. It was fabricated at the Nanjing Institute of Astronomical Optics & Technology, and the operation is jointly administered with Yunnan Astronomical Observatory. ONSET is able to observe the Sun in three wavelength windows: He I 10830 Å, Hα and white-light at 3600 Å and 4250 Å, which are selected in order to simultaneously record the dynamics of the corona, chromosphere and photosphere respectively. Full-disk or partial-disk solar images with a field of 10’ at three wavelengths can be obtained nearly simultaneously. It is designed to trace solar eruptions with high spatial and temporal resolutions. This telescope was installed at a new solar observing site near Fuxian Lake in Yunnan Province, southwest China. The site is located at E102N24, with an altitude of 1722 m. The seeing is stable and has high quality. We give a brief description of the scientific objectives and the basic structure of ONSET. Some preliminary results are also presented.

Key words: techniques: photometric — Sun: observation — Sun: telescope

1 INTRODUCTION

Recently, owing to developments in solar physics and space weather forecasting, multi-wavelength solar observations have become a pressing issue (Fang 2011). Fast evolution and fine structures of solar activities, such as flares, coronal mass ejections (CMEs) and filaments, make high spatio-temporal resolution observations an essential goal for solar observing programs (see, e.g., Fang

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et al. 2008). Correspondingly, a few new solar telescopes have been constructed in recent years. For example, in Europe, a telescope called the Chromospheric Telescope (ChroTel) started to observe the Sun in Ca II K, Hα and He I 10830 Å since April 2012 (Bethge et al. 2011); in the USA, the Synoptic Optical Long-term Investigation of the Sun (SOLIS) was equipped with a Full-Disk Patrol (FDP) module, which started to observe full disk images of the Sun at high cadence in Ca II K, Hα and He I 10830 Å in June 2011 (Pevtsov et al. 2011). Because of the geographic distribution of these solar telescopes, there is a gap in the time zone coverage of solar observations.

In order to fill in the gap so as to form a mini-network that continuously monitors the solar chromosphere and signatures of the corona, as well as carry out research on solar activities and space weather during solar cycle 24 in China, we decided to construct a new multi-wavelength solar telescope called the Optical and Near-infrared Solar Eruption Tracer (ONSET), which can conduct multi-wavelength observations in He I 10830 Å, Hα and white-light at 3600 Å and 4250 Å. The operation of the telescope is jointly administered by Nanjing University and Yunnan Astronomical Observatory. ONSET was fabricated by the Nanjing Institute of Astronomical Optics & Technology. The project was initiated in 2005, and the telescope was installed in 2011 at a new solar observing site on the bank of Fuxian Lake, 60 km from Kunming, Yunnan Province in southwest China. The site is located at E102°57′11″ N24°34′47″, with an altitude of 1722 m. The lake is about 8 km wide and 30 km long, with an average depth of 89.6 m. The seeing is stable, with the Fried parameter $r_0$ slightly larger than 10 cm on average (Liu & Beckers 2001).

In this paper, we describe the scientific objectives of the ONSET facility in Section 2, and the basic structure and specifications of the telescope are presented in Section 3. The preliminary results are given in Section 4. A summary is given in Section 5.

2 SCIENTIFIC OBJECTIVES

The main objectives of the ONSET facility are to study the following important topics.

(1) Dynamics and fast fluctuations in flares

Radiative transfer calculations indicate that different parts of the Hα line may respond on different timescales to rapid energy input (Canfield & Gayley 1987). In observations, Wang et al. (2000) found that the Hα–1.3 Å emission in a flare shows high-frequency fluctuations on a timescale of a few tenths of a second, which are temporally correlated with variations in the hard X-ray emission. Similar observations were done by Radziszewski et al. (2011) for both the line center and line wings. Numerical simulations by Ding et al. (2001) and Ding (2005) verified the close relationship between the fast variations in Hα intensity and hard X-ray emission (the latter of which characterizes the heating rate of the electron beam). Note that in some cases, the Hα line center is more easily affected by thermal conduction and some secondary effects like chromospheric evaporation and Doppler shifts. Therefore, the line wings, in particular the blue wing (Wang et al. 2000), are more suitable for showing non-thermal impulsive heating.

The He I 10830 Å line is also a potential diagnostic tool for thermal and nonthermal effects in solar or stellar flares (Ding et al. 2005). The He I 10830 Å line is a multiplet comprised of three components. This line, although formed in the upper layers of the chromosphere, is very sensitive to coronal extreme ultraviolet (EUV) irradiation. Generally speaking, there are two main ways to populate the atomic levels responsible for this line: photoionization by EUV irradiation followed by recombination and direct collisional excitation to the triplet levels (e.g., Centeno et al. 2008). During solar flares, however, a third process, collisional ionization by the electron beam followed by recombination, may be at work (Ding et al. 2005). Therefore, the line formation is complicated and one should be very cautious in interpreting the line features.

Our new telescope will have a partial-disk observation mode, with a high spatial resolution (∼1″ or better) and high temporal resolution (better than 1 s), in order to study the fine structures in solar flares. This will help reveal the physical processes related to magnetic reconnection,
energy release and energy transport in the solar atmosphere. In particular, combining these data with other observations in hard X-ray, EUV and radio, etc., we can model the thermal and non-thermal processes in flares (e.g., Fang et al. 1993; Henoux et al. 1993, 1995) and other activities.

(2) Patrol of white-light flares

White-light flares (WLFs) are generally thought to correspond to a type of the most energetic solar flare, with the continuum emissions being radiated from the photosphere or lower chromosphere. They present a major challenge to the flare atmospheric models and energy transport mechanisms (Neidig 1989; Ding et al. 1999). It has been suggested that all solar flares might be WLFs (Neidig 1989; Hudson et al. 2006), which seems to be supported by the detection of white-light emission in weak flares (Matthews et al. 2003; Jess et al. 2008; Wang 2009) and by observations of spectral irradiance (Kretzschmar 2011). However, since the discovery of the first WLF in 1859 (Carrington 1859), only around 150 WLF events have been conclusively reported so far. There are several reasons for this, including (a) the white-light enhancement in the visible continuum of a WLF is only a few percent or less, which might be below the sensitivity of some telescopes; (b) the lifetime of the white-light emission is only $\sim 1 - 2$ min, which is too short for a certain identification. On the other hand, we have to be cautious when using 1600 Å band emissions recorded by some spacecraft like TRACE and SDO/AIA to search for WLFs since this band contains emission lines, e.g., C IV. It is possible that some of the reported WLFs in 1600 Å are not real WLFs.

Depending on whether there is a Balmer jump or not, WLFs can be classified into type I and type II, respectively (Fang & Ding 1995). Whereas type I WLFs can be explained by the standard flare model, type II WLFs require in situ heating in the photosphere, with say, low-atmosphere magnetic reconnection (e.g., Li et al. 1997b; Chen et al. 2001). With two white-light wavebands inside and outside the Balmer continuum, we can distinguish which type of WLF occurred. For that purpose, we selected two white-light bands, 3600 Å and 4250 Å, that will be monitored by ONSET. With the new telescope, we expect to observe more WLFs in solar cycle 24, and to clarify some key questions regarding WLFs, such as how common WLFs are and what heating mechanism is responsible for each of the two types of WLFs.

(3) CME onset and filament activation

As the largest solar eruptions which may pose a threat to the terrestrial environment or space weather, CMEs continue to attract more and more attention (Chen 2011). The most important question related to CMEs is how the CME progenitor is triggered to erupt. Since a large fraction of CMEs originate from filaments (or prominences when they appear above the limb), it would be advantageous to monitor the activation of filaments. Various observations have revealed that before a CME is formed, the associated filament was already rising with a speed of $\sim 10 \text{ km s}^{-1}$ (e.g., Cheng et al. 2010, and references therein), as demonstrated by MHD numerical simulations (e.g., Chen & Shibata 2000). The detection of such an early slow rise will be important for a better understanding of the CME triggering process and for space weather forecasting.

For limb events, we can directly detect the rising motion from the imaging observations. However, for the disk events, especially those near the solar disk center, the detection of the slowly rising motion relies on spectrometers. One alternative way is to use simultaneous Hα imaging observations using the line center and line wings (both blue and red wings). With that, the true rising velocity of a filament on the solar disk can be measured with high precision (e.g., Morimoto & Kurokawa 2003).

(4) Moreton waves

Moreton waves are fast propagating fronts observed in the chromosphere, with an average velocity of $\sim 660 \text{ km s}^{-1}$ (Zhang et al. 2011). They typically appear dark in the Hα red wing and bright in the Hα line center and blue wing. These features can be explained well by Uchida’s model in terms of a fast-mode wave in the corona sweeping the chromosphere (Uchida 1968). There are still many puzzles that need further explanations. While Moreton waves were widely
believed to be generated by the pressure pulse in solar flares, an alternative view has appeared, which is that they are generated by the piston-driven shock as a flux rope erupts (e.g., Cliver et al. 1999; Chen et al. 2002). Another issue is the rarity of Moreton wave events. So far, it seems that less than 40 Moreton wave events have been detected since 1960. One reason is that most Hα telescopes have used the line center for observations, whereas Moreton waves are better observed near Hα ± 0.45 Å (Chen et al. 2005a).

(5) **He I 10830 waves and CME nowcast**

One of the most important discoveries of the SOHO space mission is “EIT waves” (Thompson et al. 1998). This intriguing phenomenon has sparked worldwide debates. A number of papers tried to explain EIT waves in terms of fast-mode waves (Li et al. 2012; Zheng et al. 2012); there are definitely plenty of observational features which cannot be accounted for by the fast-mode wave model, which stimulated the development of other non-wave models (see Chen & Fang 2012, for a review). For example, Chen et al. (2002) and Chen et al. (2005b) proposed a model that uses stretched magnetic field lines and claimed that EIT waves are produced by the successive stretching of the magnetic field lines straddling the erupting flux rope. Such a model can explain a variety of observations (Yang & Chen 2010; Chen et al. 2011; Cheng et al. 2012; Dai et al. 2012; Shen & Liu 2012).

EIT waves were found to be the EUV counterpart of CMEs (Chen 2009). Therefore, their appearance can be used to nowcast CMEs, especially those directed toward Earth. However, EIT waves can only be observed in EUV wavelengths, which is only feasible in space. Fortunately, the coronal brightening would result in the near infrared line He I 10830 Å being dark (Centeno et al. 2008). Therefore, even on the ground, we may detect the near infrared counterparts of EIT waves (see Gilbert et al. 2004, for an example).

On the other hand, with the same formation mechanism as Hα Moreton waves, the fast-mode coronal shock wave, when sweeping the chromosphere, might also be manifested in He I 10830 Å. Therefore, it is possible to detect two types of He I waves, the same as those seen in EUV (Chen & Wu 2011).

(6) **Filament oscillations**

Perturbations are ubiquitous in the solar atmosphere, including the continuous convective motions in the photosphere, frequent brightenings in the chromosphere and sporadic flares in the corona. Subjected to these perturbations, filaments would oscillate accordingly. On one hand, filament oscillations provide an independent approach for identifying the magnetic field across filaments (Jing et al. 2003, 2006; Isobe & Tripathi 2006; Zhang et al. 2013). On the other hand, long-lasting filament oscillations might be one of the precursors of CME eruptions (Chen et al. 2008).

(7) **Other fine structures**

In the solar lower atmosphere, there is a pool of small-scale eruptive events, including microflares (Fang et al. 2006a), Ellerman bombs (Chen et al. 2001; Fang et al. 2006b) and coronal bright points (CBPs, Zhang et al. 2012b). While Ellerman bombs can be directly observed at the wings of the Hα line, microflares and coronal bright points are often observed in X-ray, but sometimes they show brightenings in Hα (Jiang et al. 2012; Zhang et al. 2012a). Besides, CBPs appear as dark points in He I 10830 Å (Li et al. 1997a).

It is generally believed that coronal holes are the source of the fast solar wind, which is important for space weather research. Using He I 10830 Å images, we can clearly detect coronal holes and trace their evolution.

### 3 BASIC STRUCTURE AND SPECIFICATIONS

Figure 1 shows the building that houses ONSET near Fuxian Lake (left panel) and the telescope inside the dome that opens like a blossoming flower (right panel). The ONSET telescope con-
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The building that houses ONSET near Fuxian Lake (left) and the telescope inside the dome that opens like a blossoming flower (right). The left picture was taken during the construction of the building.

The ONSET facility consists of four tubes: (1) a near-infrared vacuum tube with an aperture of 27.5 cm, observing at He I 10830±4.0 Å with an FWHM of 0.5 Å; (2) a chromospheric (Hα) vacuum tube with an aperture of 27.5 cm, observing at 6562.8 ± 2.5 Å with an FWHM of 0.25 Å; (3) a white-light vacuum tube with an aperture of 20 cm, observing at the wavelengths 3600 Å and 4250 Å with an FWHM of 15 Å; and (4) a guiding tube with an aperture of 14 cm, observing at the wavelength 5500 Å.

The former two tubes are equipped with two Lyot-type filters, while the latter two use interference filters. The first three tubes are vacuum ones, and they provide full-disk (extending up to 1.3\(R_\odot\)) or partial-disk images with a field of view of 10\('\) \times 10\('\). The three wavelength windows can work independently and simultaneously. Two observation modes (full-disk and partial-disk) can be switched back and forth according to scientific requirements. All the observations are controlled by a computer and the observing program is flexible. Our research program plans to perform routine observations to acquire 8–10 full-disk images every 1 min in the Hα line center and its two wings at ±0.5 Å, the He I 10830 Å line center and its two wings, and two white-light wavelengths. We can also carry out partial-disk observations of solar activities with high spatial (∼1″ or better) and temporal (0.1 to 1 s) resolutions.

The ONSET facility has one PIXIS 2048BR CCD for Hα, with 2048×2048 pixels (the pixel size is 13.5 μm), one PCO4000 CCD for white-light observations, with 4008×2672 pixels (the pixel size is 9 μm) and one VersArray CCD for 10830 Å observations, with 1340×1300 pixels (the pixel size is 20 μm). The diameters of all solar images are about 24 mm at the focal plane.

A series of software programs are being developed (e.g., Hao et al. 2013), including data archiving, a search engine that can be applied to archived data, data calibrations, automatic detections of solar activities (e.g., Moreton waves and He I 10830 waves), velocity measurements, and a remote control system, etc.
4 PRELIMINARY RESULTS

Since April 2011, we have conducted test observations of the new telescope, and obtained some preliminary results. Figure 4 shows an H$\alpha$ partial-disk image and a white-light partial-disk image at 4250 Å, where the fine structures of a sunspot and the background granules are clearly visible. It seems that the image quality is very good. In particular, a WLF was successfully observed on 2012 March 9, which is the first flare detected by the ONSET facility (Hao et al. 2012). Continuum emissions clearly appear at the 3600 Å and 4250 Å wavebands. The peak enhancements at these two bands are 25% and 12%, respectively. This event shows clear evidence that the white light emission is caused by energetic particles bombarding the solar lower atmosphere.

Since the beginning of 2013, ONSET has started to make routine observations. Figure 5 illustrates an H$\alpha$ image (left panel) and an He I 10830 Å image (right panel), which is the first 10830 Å image ever observed in China.
Fig. 4 An $\text{H}\alpha$ partial-disk image (left) and a 4250 Å partial-disk image (right) observed by using ONSET. The image in the left panel was taken at 07:05:25 UT on 2011 April 21 with a field of view of 10' × 10', whereas that in the right panel was acquired at 14:00:52 UT on 2013 May 27 with a field of view of 210'' × 160''.

Fig. 5 An $\text{H}\alpha$ (left) and an He I 10830 Å (right) image observed by ONSET. The image in the left panel was taken at 03:09:36 UT on 2013 April 30, whereas that in the right panel was acquired at 03:39:21 UT on 2013 March 13.

ONSET is dedicated to a wide variety of solar activity research, especially through joint observations with other ground-based and space-borne instruments. The data from routine observations will be open and available on the internet (http://sdac.nju.edu.cn). Everyone is welcome to use ONSET data and help develop software programs for the data reduction process.

5 SUMMARY

After making efforts over the past several years, we have successfully constructed ONSET at the new solar observing site near Fuxian Lake, which is currently the best site for solar observations in China. The ONSET facility consists of four tubes, and three of them are vacuum ones. The telescope
can provide 8–10 solar images at He I 10830 Å (line center and blue/red wings), Hα (line center and blue/red wings) and white-light at 3600 Å and 4250 Å. The wavebands were selected in order to simultaneously observe the dynamics in the corona, chromosphere and photosphere. With the accumulation of observational data, our research program expects to yield the following results.

1. Fast variations of solar flare emissions will be examined in a systematic way in order to indirectly derive nonthermal parameters in solar flares. In particular, the different responses in Hα and He I 10830 Å to nonthermal particles can be compared.

2. A catalog of white-light flares will be compiled, with classification into type I and type II events. The relationship between white-light enhancements and soft X-ray intensity can be scrutinized.

3. Early slow rising motion of erupting filaments can be detected with high cadence, which provides real-time monitoring of the onset of filament eruptions and CMEs.

4. Both Hα Moreton waves and “EIT waves” might be recorded by He I 10830 Å images, which will help clarify the possibly different natures of the two wavelike phenomena.

5. Both transverse and longitudinal filament oscillations will be routinely recorded, which paves the way towards prominence seismology.

6. A large number of small-scale eruptions will be observed, including Ellerman bombs and CBPs.

The preliminary results demonstrate that the quality of the solar images is high and good enough for scientific research. The ONSET facility has performed routine observations since 2013. The data will be open and available on the internet. Everyone is welcome to use the ONSET data and help develop software programs.

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