Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 315-318

The new Solar Ultraviolet to Near-infrared Spectrometer — SUNS

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Abstract. Desde a primeira observação de uma explosão solar em 1859 por Carrington e Hodgson, explicar a origem do excesso de emissão contínuo visível (white-light flares, WLFs) continua sendo um desafio na física desses eventos. Identificar esse mecanismo de radiação é crucial para compreender o transporte e deposição de energia na atmosfera da estrela. No entanto, dados espectrais para WLFs solares são relativamente raros e insuficientes para dissipar a ambiguidade de sua origem: radiação de corpo negro fotosférica ou contínuo de Paschen a partir da recombinação de hidrogênio na cromosfera. Discutimos os desafios nas observações e na modelagem de WLFs solares e estelares, em termos dos processos físicos e da deposição de energia na atmosfera das erupções e de observações anteriores. Devido à falta de observações solares com resolução espectral cobrindo toda a faixa visível, apresentamos um novo telescópio para suprir esta demanda: o Solar UV-NIR Spectrometer (SUNS), desenvolvido e integrado na sede do Centro de Rádio Astronomia e Astrofísica Mackenzie (CRAAM), em parceria com o Instituto Steiner, com financiamento da FAPESP e da MackPesquisa. Apresentaremos suas características ópticas, mecânicas, espectrais, condições de observação, etapas futuras e resultados esperados. O SUNS fornecerá espectros resolvidos na faixa visível, o que nos permitirá colocar os modelos de emissão do contínuo visível atuais em teste e caminhar em direção a uma solução para o mistério de mais de 165 anos da origem dos WLFs.

Resumo. Since the first observation of a solar flare in 1859 by Carrington and Hodgson, explaining the origin of the excess visible continuum emission (white-light flares, WLFs) remains a challenge in the understanding of these events. Identifying the radiation mechanism involved is crucial for understanding the transport and deposition of energy in the solar atmosphere. However, spectral data for solar WLFs are relatively rare and insufficient to dispel the ambiguity of their origin: photospheric blackbody radiation or Paschen continuum from hydrogen recombination in the chromosphere. Due to the lack of solar observations with spectral resolution covering the entire visible range, we present a new telescope to meet this demand: the Solar UV-NIR Spectrometer (SUNS), developed and integrated at the Center for Radio Astronomy and Astrophysics Mackenzie (CRAAM), in partnership with the Steiner Institute, with funding from FAPESP and MackPesquisa. We will present its optical, mechanical, and spectral characteristics, observation conditions, future steps, and expected results. SUNS will provide resolved spectra in the visible range, which will allow us to test current visible continuum emission models and move towards a solution to the more than 165-year-old mystery of the origin of WLFs.

Keywords. Instrumentation: spectrographs – spectroscopy – Sun: activity – Sun: flares

1. Introduction

The first recorded solar flare, on September 1, 1859, by Carrington (1859) and Hodgson (1859), was observed in visible light (*white-light*). Since the 1960s, numerous observational and theoretical studies have attempted to explain the generation of excess visible light caused by the flares, but without yet finding a definitive solution (Hudson et al. 2010). Fig. 1 brings together the three most commonly used visible spectra for interpreting the origin of *white-light flares* (WLFs). From these (and other) studies, two alternatives emerged that describe the most plausible scenarios: blackbody radiation caused by heating of the photosphere or hydrogen recombination continuum in the chromosphere. The limitation of the first case can be summarized as a matter of energy transport: none of the energy transport mechanisms typically discussed in solar flares has the capacity to deliver the energy necessary to cause photospheric heating in order to explain the observations. In the second case, the problem is observational: the few spectra obtained in the visible spectrum are not completely compatible with the recombination spectrum of H (Hiei 1982), as is the case with the third spectrum in Fig. 1. One of the fundamental questions still open is verifying how much the higher-order lines of the Balmer series of H accumulate near the Balmer limit (364.6 nm), preventing its detection in observations, as in the case of the first spectrum in Fig. 1. On the other hand, a study by Kerr & Fletcher (2014) indicates that the two mechanisms would be consistent with the observations of a particular event, but only three spectral data points across the visible range. Unfortunately, the lack of spectral observations in the visible range has hindered the advancement of this line of research.

Like WLFs, observations of high-order lines of the Balmer series of H during flares are rare; we highlight here unique examples discussed by Fritzová-Švestková & Švestka (1967) and Procházka et al. (2017). In the 1960s, the idea of obtaining an electron-density diagnosis from measurements of the widths of high-order lines (above H9) in the Balmer series of H was proposed. The method assumes constant electron temperature and that the higher-order lines are in the optically thin regime. Electron densities on the order of 3×10^{13} cm^{-3} in flares were obtained by this method, with uncertainties on the order of 30% (Fritzová-Švestková & Švestka 1967); such values for electron density were used for analysis and discussion of WLF formation (Machado & Rust 1974; Neidig 1983). Procházka et al. (2017) presented observations of the Balmer series of H during two intense solar events, but with uncalibrated data. These observations were the result of a unique campaign with a spectrometer

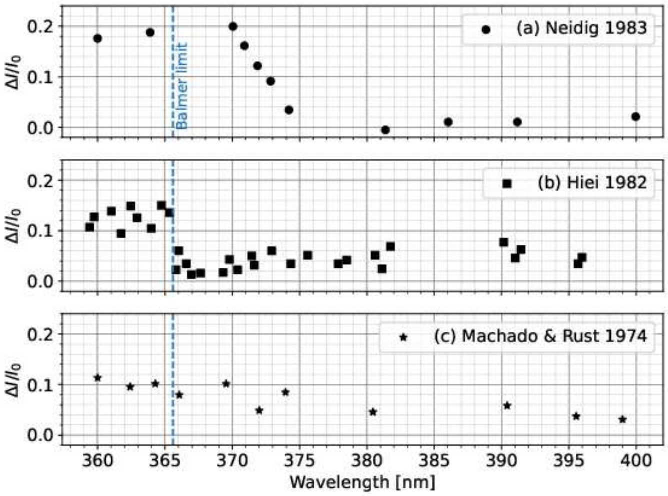

Figure 1. Observed WLF spectra compiled using data from Neidig (1983), Hiei (1982), and Machado & Rust (1974).

Figure 2. Hale-type heliostat used in OSM.

Table 1. Characteristics of the Spectroscopy Module (SM).

Angular size of the Sun	~30 arcmin
Telescope aperture (pupil)	46 mm
Focal distance	850 mm
F-number	18.576
Numerical aperture (NA)	0.027
Optical fiber diameter	0.600 mm
Size of the projected solar image	7.417 mm
Field of view (FOV)	2.427 arcmin
Spectral range (nominal)	200 to 1000 nm

installed at the Ondrejov Observatory (Kotrč et al. 2016) in the Czech Republic, which is no longer in operation. However, these observational results indicate the importance of including the Balmer series in studies of the optical spectrum of solar flares, especially when comparing the observational results (and their interpretations).

We propose investigating a spectral range that has, to some extent, been ignored by the scientific community: the visible spectrum, which spans from the near-infrared (NIR) to the ultraviolet (UV). The new telescope, a spectrometer covering the entire visible spectrum, named Solar UV-NIR Spectrometer (SUNS), has been designed and assembled at the Mackenzie Solar Observatory (Observatório Solar Mackenzie, OSM), at the CRAAM headquarters on the Higienópolis campus of Mackenzie Presbyterian University (MPU). The development of SUNS was carried out in partnership with the Steiner Institute and is now in its commissioning phase. In the next phase, we will conduct observations to evaluate the scientific quality of the data, develop data calibration methods that account for atmospheric attenuation and instrumental losses, and refine the observation and pointing methods.

2. The Mackenzie Solar Observatory

Currently, the OSM is composed of the following modules: the Infrared Imaging Module (IM) and the Hα Imaging Module (HM). The guiding and control of the Sun's rotation is performed by a Hale-type heliostat, as shown in Fig. 2, and a Hinode SG - Solar Autoguider positioning correction system from Astro Hutech. The infrared module (MI) consists of a 150mm f/8 Newtonian telescope containing a 30 THz (10 μm) Teledyne FLIR A20 infrared camera, SP30T, with the aim of observing this range between visible and radio waves to perform unprecedented diagnoses of the occurrence of solar flares associated with the magnetic fields of active regions Kudaka et al. (2015). The H-alpha imaging module (narrow filter at 656.3 nm) consists of a Lunt refractor telescope with a 60 mm objective and a diagonal mirror containing an Ethalon LS60FHa front filter and a B1200 diagonal attenuator filter, with a Lumenera L075C CCD camera, intended to observe structures in the chromosphere such as spots, filaments, and prominences Kudaka et al. (2015). SUNS has been assembled into a new spectroscopy module (SM), described in the next section.

3. SUNS optomechanical design and first-light

The concept of the Spectroscopy Module (SM) consists of a dedicated refractive telescope, a translational optomechanical stage coupled to an optical fiber for selecting the area of interest in the Sun for obtaining the solar spectrum, a commercial spectrometer, and a real-time monitoring system of the Sun and the spectral area of interest to identify which region of the Sun is being spectrally obtained. An Ocean Insight HR4000CG-UV-NIR spectrometer was acquired for solar observations through the FAPESP thematic project 2013/24155-3. The spectrometer operates across the entire visible spectrum (200 nm to 1 μm, nominally digitized to 3647 values) with sufficient resolution to identify and study atomic spectral lines produced in the solar atmosphere. Considering that the average angular size of an active region is approximately 1.5 to 2 arcmin, a survey of the optical system necessary to meet this requirement was carried out, as shown in Table 1. Given the angular size of the Sun and the average size of an active region, an optical fiber with a diameter of 0.6 mm can resolve objects up to 2.43 arcmin. If it is necessary to increase to 1 mm or decrease to 0.2 mm, considering the existing fibers, the field of view would be 4.04 arcmin or 0.81 arcmin, respectively.

The SM operates in parallel with the other imaging modules, IM and HM, as shown in the diagram in Fig. 3, thereby increasing the functionality of the OSM. The only necessary change in the current OSM setup was replacing the flat mirror that redirects the light beam to the HM with a beam splitter, to install the SM in a region with easier access to the equipment controls. After reflection on the first flat mirror at the IM telescope's entrance,

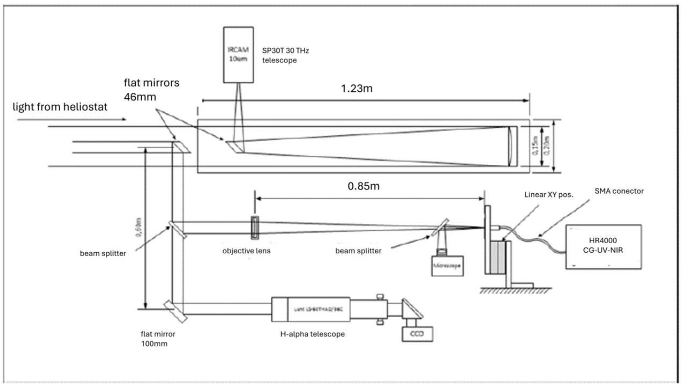

Figure 3. General diagram of the Mackenzie Solar Observatory (OSM) with the inclusion of the Spectroscopy Module (SM).

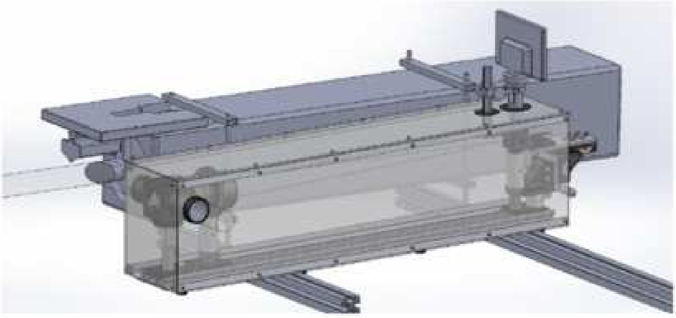

Figure 4. General view of the Mackenzie Solar Observatory (OSM) including the 3D model of the Spectroscopy Module (SM).

the light reflected by the beam splitter is directed to the SM telescope's entrance, which consists of an achromatic objective. Its focal plane consists of a flat, reflective projection screen with a central hole, in which an SMA connector is fixed on its rear face for optical fiber installation, aligned with this hole. Thus, when installing the fiber, the tip's surface is aligned with the plane of the projection screen. Once the image of the Sun is projected onto this plane, part of the Sun's radiation is coupled to the fiber, which then feeds the commercial spectrometer. The entire flat window system is installed on an XY stage (perpendicular to the optical axis) to select the region of interest on the Sun. A beam splitter is installed just before the telescope's focal plane, which coincides with the projection screen. It enables, via reflection off this screen, imaging of the Sun using a low-cost commercial microscope with a USB connection. This functionality allows the user to identify in real time which region of the Sun is being spectrally obtained.

The SM comprises seven parts: Base, Pedestals, Input Splitter, Objective, Output Splitter, Focal Plane, and Cover. The Base consists of a rail that ensures the alignment of the optical axis. The Input Splitter, Objective, Output Splitter, and Focal Plane are all supported by the Pedestals. The entire system is protected from stray light and dust by an acrylic box structure as shown in Fig. 4, containing inlet and outlet openings for the beam from the heliostat, and an outlet for the optic fiber cable, which is connected to the Ocean Insight HR4000CG-UV-NIR spectrometer. Fig. 5 shows the side and perspective views of the SM with indications of the parts that make up the system. Fig. 6 shows SUNS during its assembly phase, which was then incorporated into the OSM with the SP30T and Hα telescope, as shown in Fig. 7.

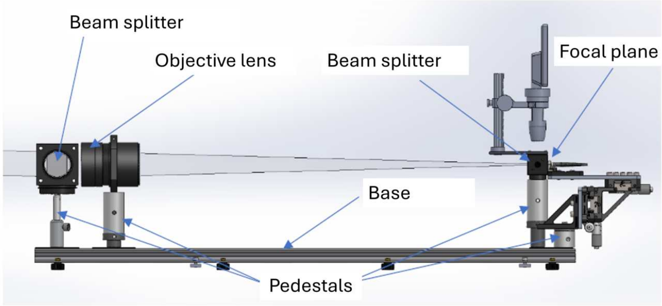

Figure 5. Side view of the SM without the cover.

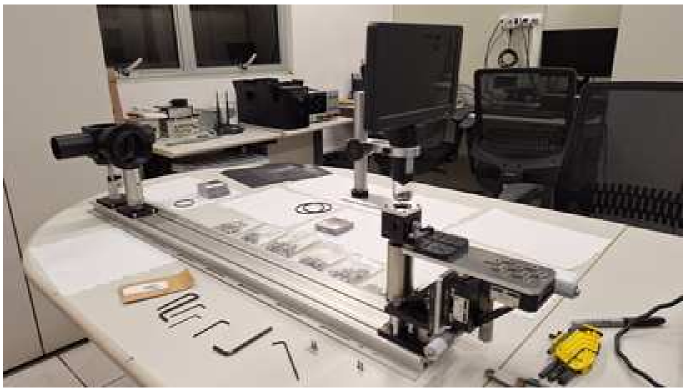

Figure 6. Assembly phase of SUNS at the OSM.

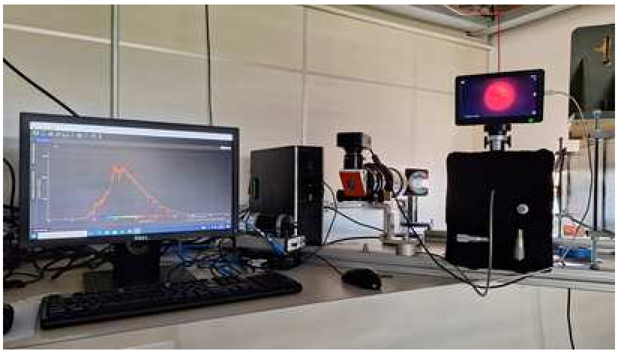

Figure 7. New arrangement of telescopes at OSM, with the Hα, SP30T and SUNS telescopes.

With the completion and assembly of SUNS, we carried out the first official observation, its first light, on the International Day of Light, May 16, 2025, recording the solar spectrum, as shown in Figure 8.

4. SUNS logo design

In collaboration with the Design undergraduate program at Mackenzie Presbyterian University (UPM), we participated as clients in a course taught by professors Grace Kishimoto and Marcos Aurélio "Kito" Castanha Júnior. The class was divided into seven groups that proposed logos for SUNS. Three meetings were held: presentation of SUNS and CRAAM, brand needs and uses, and preferred styles; meetings with each group to discuss preliminary proposals; and presentation of each group's final proposals, evaluated by representatives of the SUNS team. The chosen proposal is shown in Fig. 9, developed by Fernando Tetsuo.

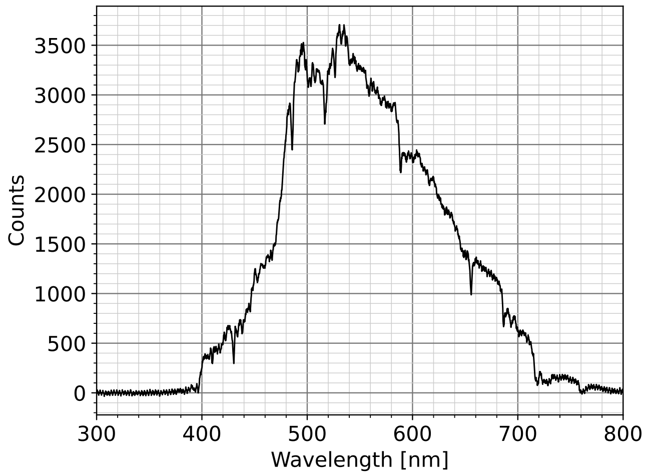

Figure 8. First solar spectrum recorded by SUNS, on the International Day of Light, May 16, 2025.

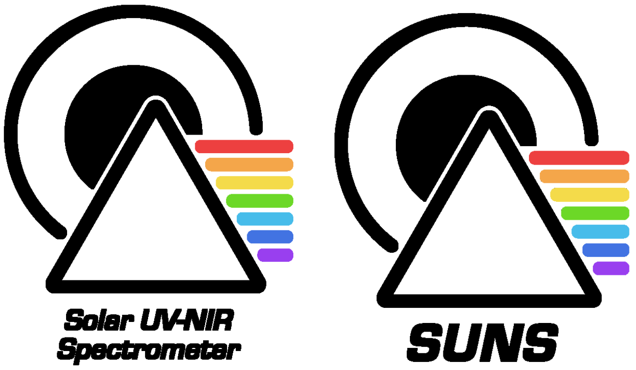

Figure 9. SUNS logo developed by Design undergraduate student Fernando Tetsuo.

5. Concluding remarks and future work

Given the lack of spectral data in the visible range to study the physics of white-light flares in the Sun, we proposed a low-cost prototype spectrometer, based on commercially available parts, the Solar Ultraviolet to Near-infrared Spectrometer, SUNS. It was projected and assembled between 2023 and 2025, entering its commissioning phase on the 16th of May 2025, the International Day of Light.

The commissioning phase includes the development of automatic data acquisition software, data calibration methodology, and observation planning. Currently, spectra are recorded using standard OceanView software, which allows adjusting the integration rate and recording cadence of the spectra. However, each spectrum is individually saved to disk, limiting the cadence to the computer's write speed. New acquisition software will be developed by graduate students to exploit accumulation and temporal integration in RAM before saving files to disk, thereby increasing the system's cadence. The Ocean software development kit (SDK) has already been acquired for this purpose. Another step is the development of the data calibration methodology and software to convert digitized counts to physical units, and to account for instrumental losses (lenses, filters, optical fibers, beam splitters, etc.) and atmospheric attenuation. For the latter, we will use the software MODTRAN (MODerate resolution atmospheric TRANsmission), which allows modeling the spectral transmission of the Earth's atmosphere under various conditions. With the current solar activity cycle still in its maximum phase, we anticipate detecting at least a few flares to verify the full scientific potential of the SUNS prototype.

Acknowledgements. We acknowledge support from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (contract 305808/2022-2), Fundo Mackenzie de Pesquisa e Inovação (MackPesquisa) project 231017, and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) contracts 2013/24155-3 and 2022/15700-7. We thank Grace Kishimoto, Marcos Aurélio "Kito" Castanha Júnior, and Beatriz Duque for their support with the SUNS logo design, and Fernando Tetsuo for the final logo design.

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