Advancing **High-Resolution Studies of Sunspot Penumbra** Formation and Decay:

new opportunities for the solar community provided by **IBIS2.0**

an upgrade of the Interferometric BIdimensional Spectrometer

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Abstract

Sunspot formation is the primary manifestation of magnetic flux emerging from the convection zone into the solar atmosphere. Among the various features of sunspots, the penumbra is particularly intriguing due to several unresolved issues, such as the interpretation of its formation and decay processes and understanding its bolometric brightness. Recent high-resolution spectropolarimetric observations have proposed two scenarios for penumbra formation: the trapping of emerging horizontal field lines by a magnetic canopy and the sinking of existing magnetic fields from the chromosphere into the photosphere. These processes remain incompletely understood, although we recently provided new findings on the properties of the penumbral magnetic fields in the chromosphere at atmospheric heights unexplored in previous studies. Additionally, studies on the dynamics of the Evershed flow during penumbra formation have provided some insights, but many questions remain. We present our results obtained on these topics using the Interferometric BIdimensional Spectrometer (IBIS). The IBIS 2.0 project, an upgrade of IBIS that operated at the DST from 2003 to 2019, aims to address these gaps in knowledge. The upgraded instrument, to be installed at a telescope in the Canary Islands, will provide detailed spectropolarimetric data, capturing information along both photospheric and chromospheric lines in the 580-860 nm range. This will enable a comprehensive examination of magnetic flux emergence and its interactions with the magnetic canopy. Overall, IBIS 2.0 will significantly enhance our understanding of sunspot penumbra formation and decay, providing a powerful tool for high-resolution solar research.

IBIS2.0: an upgrade of the Interferometric BIdimensional Spectrometer

The **IBIS 2.0 project upgrades the Interferometric BIdimensional Spectrometer** (IBIS, Cavallini 2006), which was operated at the Dunn Solar Telescope (DST) of the National Solar Observatory (NSO) from 2003 to 2019, for installation in the Canary Islands. The instrument combines **two tunable Fabry-Perot interferometers** used in classical mount**,** a set of **narrowband interference filters** (FWHM approx. 0.3-0.5 nm), **a polarimetric unit** realized with 2 Liquid Crystal Variable Retarders and a Polarizing Beam-splitter**, fast cameras**, and a **suitable control** for the acquisition of **high-resolution spectropolarimetric data** of the **photosphere and chromosphere**.

A new opto-mechanical design was developed for the **installation of IBIS2.0 (Figure 1) at a telescope in the Canary Islands**. To this aim, **each component of IBIS 2.0 and whole instrument were modeled in SolidWorks**.

IBIS 2.0

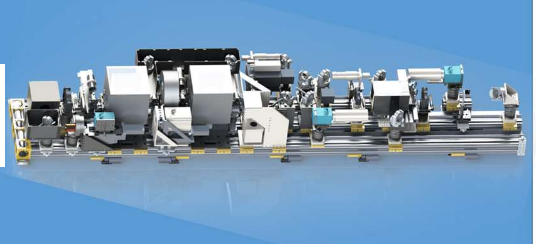

Figure 1. New opto-mechanical design of IBIS 2.0.

See Ermolli et al. 2020, 2024 and Viavattene et al. 2022 for further details.

The onset of the classical Evershed flow

We used **high spatial, spectral, and temporal resolution IBIS data** to study the variations of line of sight photospheric plasma flows during the formation of the penumbra around a pore.

- We understood that the **change from counter Evershed flow**, visible before the penumbra appears, **into the classical Evershed flow** may be a **signature** of the **formation** of penumbral **filaments**.
- The inversion of photospheric IBIS data allowed us also to **reconstruct how the uncombed configuration of the magnetic field forms during the new settlement of the penumbra**, i.e., the vertical component of the magnetic field seems to be progressively replaced by some horizontal field lines, corresponding to the intraspines.

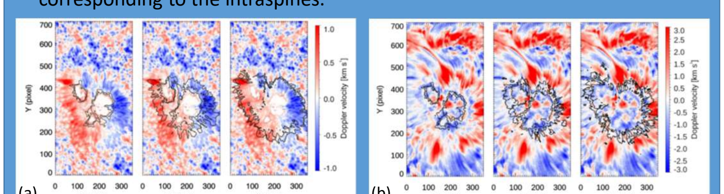

Figure 3. Doppler velocity map obtained by the monochromatic images taken on May 18 at 14:42 UT along the Fe I line at 630.25 nm (a) and along the Hα line at 656.2 nm (b).The contours of the features corresponding to the head (left panel), body (central panel), and tail (right panel) of the penumbral filaments are overplotted to the velocity map (from Romano et al. 2023).

- We found that **during the stable phase** of the penumbra **two opposite Evershed regimes** (inverse and classical) work next to each other, without overlapping, and both contribute to the downflow around sunspots.
- These **results confirm the uncombed model of the sunspot penumbra** and provide further hints that the **downflow around sunspots may be ascribed to the magnetic field dragging the plasma down**.

See Murabito et al. 2016, 2018 and Romano et al. 2020, 2023 for further details.

Sunspot penumbra formation

IBIS spectropolarimetric observations of the evolution of the magnetic field and plasma flows have supported the idea that the penumbra forms due to a **change in the inclination of the magnetic field canopy** until it reaches the photosphere.

- Before the penumbra formation we detected an **annular zone** of 3"-5" width around the sunspot.
- This zone is characterized by an **uncombed structure** of the magnetic field although no visible penumbra has formed yet.
- We detected the presence of several **patches** at the edge of the annular zone, with a typical size of about **1"**.
- These patches are **characterized** by a rather **vertical** magnetic field with polarity **opposite** to that of the pore (see Figure 2).
- We interpreted these features as **portions of the pore magnetic field lines returning beneath the photosphere** being progressively stretched and pushed down by the overlying magnetic fields.

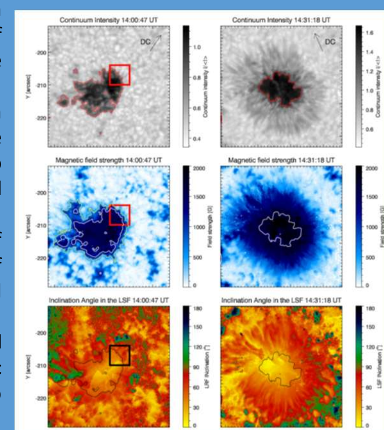

Figure 2. Maps of intensity, magnetic field strength, and inclination angle on 2012 May 28 at 14:00 UT (left, before penumbra formation) and on 2012 May 29 at 14:31 UT (right, after penumbra formation), obtained from the SIR inversion of the Stokes profiles of the Fe I 630.25 nm line acquired by IBIS (from Murabito et al. 2016).

See Romano et al. 2013, 2014 and Murabito et al. 2016 for further details.

New opportunities for the solar community

Despite these breakthroughs, the **fundamental scales** of observed processes and the **coupling between different heights** in the Sun's atmosphere remain **unresolved**, necessitating **further high-resolution spectropolarimetric observations of the photosphere and chromosphere**.

IBIS 2.0 will be used to acquire these data, also in coordination with other ground- and space-based instruments observing the Sun in different energy bands and over other time windows, and employing different measurement methods and polarimetric sensitivities.

IBIS 2.0 will offer new opportunities for the study penumbra formation and decay processes, among many other scientific topics in solar physics for a better knowledge of plasma properties at different heights in the solar atmosphere.

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