Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

WEAVE monitoring of stellar clusters with O stars

Holgado, G.[1], **Maíz Apellániz, J.**[2], **Fariña, C.**[3,1], **Molina Lera, J. A.**[4], **and Pantaleoni González, M.**[5]

[1] Instituto de Astrofísica de Canarias, IAC, Avenida Vía Láctea, E-38205 La Laguna, Tenerife, Spain
[2] Centro de Astrobiología (CAB), CSIC-INTA, Campus ESAC, C. Bajo del Castillo s/n, E-28692 Madrid, Spain
[3] Isaac Newton Group of Telescopes, Roque de Los Muchachos Observatory, 38700 La Palma Island, Santa Cruz de Tenerife
[4] Instituto de Astrofísica de La Plata (CONICET–UNLP), and Facultad de Ciencias Astronómicas y Geofísicas (UNLP), Paseo del Bosque s/n, La Plata B1900FWA, Argentina
[5] University of Vienna, Department of Astrophysics, Türkenschanzstrasse 17, 1180, Vienna, Austria

Abstract

The MONOS project has obtained WEAVE LIFU observations to study the cores of nine stellar clusters containing O and B stars. Most O stars form in multiple systems, which allows for the determination of stellar masses through their orbits. However, this process is complicated by the wide range of orbital periods and the presence of complex systems like triples and higher-order multiples. The initial analysis focuses on assessing the quality of the WEAVE LIFU spectra and providing spectral classifications. Future work aims to determine spectroscopic binarity and study stellar orbits using radial velocity and photometry from TESS and *Gaia*.

1 Introduction

O-type stars are pivotal to understanding stellar evolution and dynamics ([2, 4]). These massive stars significantly impact their environments ([1]). O-star clusters also provide key insights into high-mass star properties and their interactions ([5]).

Multiplicity is one of the most critical factors in O-star evolution, with 45-75% of OB stars having companions ([14]), shaping their life paths and affecting their environments. The MONOS project ([10]) focuses on O-type spectroscopic binaries in the northern hemisphere.

This new phase of MONOS leverages WEAVE's advanced capabilities to study clusters of interest and explore multiplicity and spectral classification.

2 WEAVE LIFU campaigns

O stars often form in densely populated stellar clusters with hierarchical systems, making WEAVE LIFU an invaluable tool for studying these regions. Its ability to capture high-quality spectroscopy of multiple sources within a single field of view offers significant advantages for the MONOS project. We are using WEAVE LIFU to conduct multi-epoch spectroscopy of nine carefully selected stellar clusters.

WEAVE LIFU's strength lies in its capacity to observe numerous sources in a cluster, far exceeding the single-star focus of fiber or long-slit spectrographs. It also allows for efficient subtraction of nebular lines, such as H and He I, using adjacent star-free fibers, enhancing our study of stellar multiplicity and massive star evolution.

We secured observation time for the 2023 and 2024 open time campaigns, selecting clusters from the GOSC and ALS catalogs ([6, 13]) with at least three O stars and a declination > -25º. So far, we have identified nine suitable northern hemisphere clusters for observation, with current progress summarized in Table 1. In addition, the average number of interesting objects in our field of view includes the minimum three O-type stars along with approximately 20 additional B-type stars.

Table 1: 2023 and 2024 observations summary.
Various exposure times were included after reduction to address saturation issues. The blue and green high-resolution observations were taken with the same exposure time.

Name	**Center Coords**	**LowRes_ExpT**	**HighRes_ExpT**	**LowRes**	**HighRes(B+G)**
Villafranca_O-005	17:24:42.5 -34:12:14.4	6x420s	3x1020s	0	0
Villafranca_O-007	20:33:10.3 +41:13:12.0	4x720/6x420s	3x1020s	1/1	1+3
Villafranca_O-008	20:33:16.3 +41:18:57.6	12x100s	6x420s	1	1+1
Villafranca_O-009	18:20:32.2 -16:10:30.0	6x420s	3x1020s	0	0
HD_167_834	18:17:32.9 -12:06:10.8	10x333s	6x420s	1	0
NGC_6604	18:18:04.6 -12:14:24.0	10x180/14x50s	12x100s	1/1	1+1
BD_+55_2722	22:19:01.4 +56:07:26.4	6x420/7x333s	3x1020s	1/1	0
Pacman_nebula	00:52:47.5 +56:37:26.4	5x180/12x100s	6x420s	2/1	3+1
BD_+00_1617	06:48:49.4 +00:22:37.2	6x420s	4x720s	1	5+7

As shown in the table, the aim is to obtain one or two low-resolution exposures, followed by several epochs at high resolution. Each observation consists of multiple exposures, typically between 4 and 12 in the red range and an additional 4 to 12 in the blue or green ranges, employing a dithering pattern.

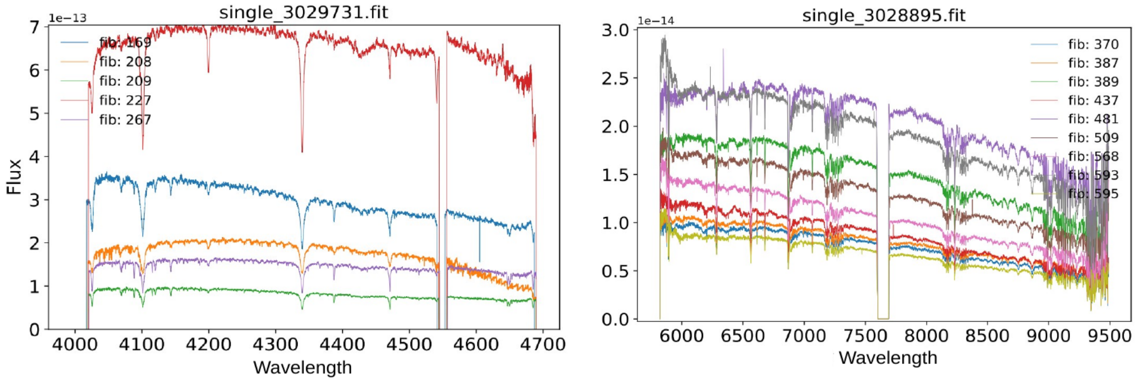

Figure 1: Examples of spectra for fibers with S/N > 30 for a low-resolution blue observation (left) and a high-resolution red observation (right).

3 Assessment of Spectral Data

In the initial stages of our research, we aim to utilize the data obtained from the WEAVE LIFU pipeline to achieve two primary objectives. First, we will assess the capabilities and limitations of the generated spectra, specifically examining potential issues related to flat field corrections, sky subtraction, and the appearance of diagnostic lines. Second, we will focus on providing accurate spectral classifications based on the analyzed data.

3.1 WEAVE L1 data

L1 data is defined as consisting of several individual spectra (about 600, one per fiber in the FoV including sky bundles), either in the red or blue/green range, along with two stackcubes (one per region of the sky), all formatted as ".fit" files. Stackcubes are designed to accumulate all spectra within a specified area, incorporating data from all pointings. For now, we are focusing on the analysis of single L1 ".fit" files, the individual spectral data, prior to delving into the more complex stackcubes.

One of the initial findings is that the S/N exceeded our expectations, resulting in saturation and requiring us to reduce the exposure times, as indicated in the table 1.

We have obtained high-quality examples with strong S/N (calculated by CASU and included in the .fit file table extension) in both high and low resolution. The wavelength range of the red and blue observations at both resolutions meets expectations. Notably, we have observed that the inter-CCD gap may occasionally be slightly shifted, but the displacement is minimal (Fig. 1).

3.2 Artifacts

We identified some types of artifacts in the spectra, the primary one being what we refer to as "bites." These segments show a sudden drop in signal strength that is lower than expected.

They appear to be associated with stars exhibiting high counts in the red spectra, although the correlation is not always consistent. For instance, in spectra of the same star taken at different epochs, those with higher counts do not exhibit the issue, while those with lower counts do, with this pattern repeating inconsistently across wavelengths (Fig. 2). Also, we discovered these artifacts in observations that did not experience saturation. We consider that the origin may be related to the trace extraction process from the CCD image.

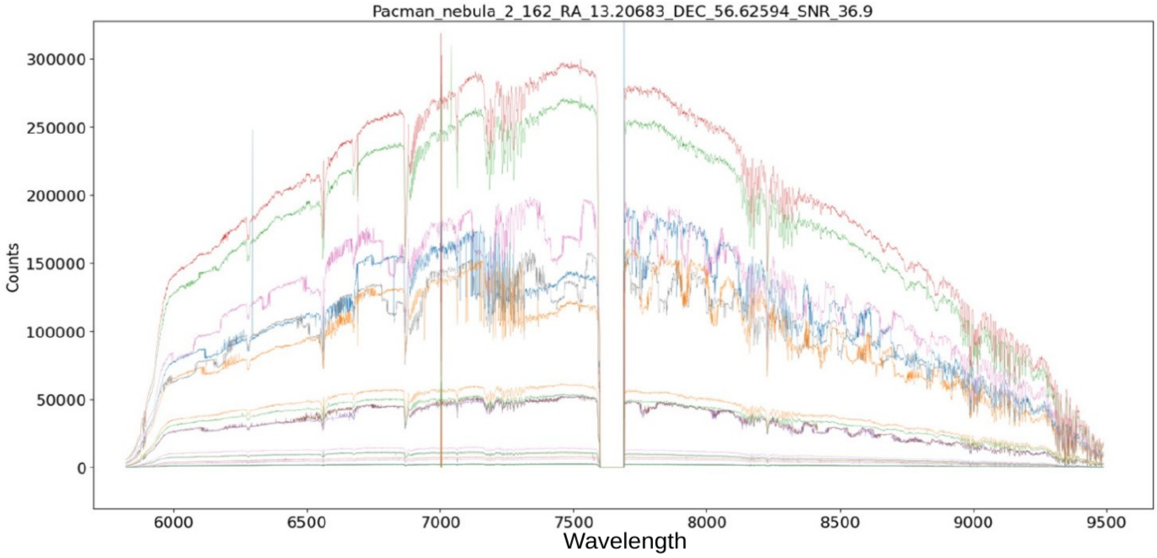

Figure 2: Examples of "bites" artifact for the same star across different observations and fibers.

Additionally, we encountered flat field issues in two blocks of observations. A peculiar structure emerges around 5000 Å in the low-resolution blue observations, particularly for data collected on a specific date. These problems underscore the necessity of thoroughly reviewing the spectra before relying on the information provided in L2, the tables generated by the pipeline. We have contacted the people responsible of the pipeline, who are aware of these issues and are actively addressing them. They have informed us that these concerns will be rectified in the second reprocessing, which will be available in November.

3.3 Spectral classification and binary detection

As previously mentioned, we aim to explore the feasibility of performing spectral classification and radial motion analysis. We use HD 5005 D, an O star in the Pacman Nebula, as a case study (Fig. 3). We have gathered all the spectra corresponding to its coordinates to analyze the available spectral lines and assess their potential for spectral classification and radial velocity variability.

In the spectral classification region, we have access to diagnostic lines including He I, He II, Carbon and Silicon lines (in this case), etc, and the hydrogen series. We have marked

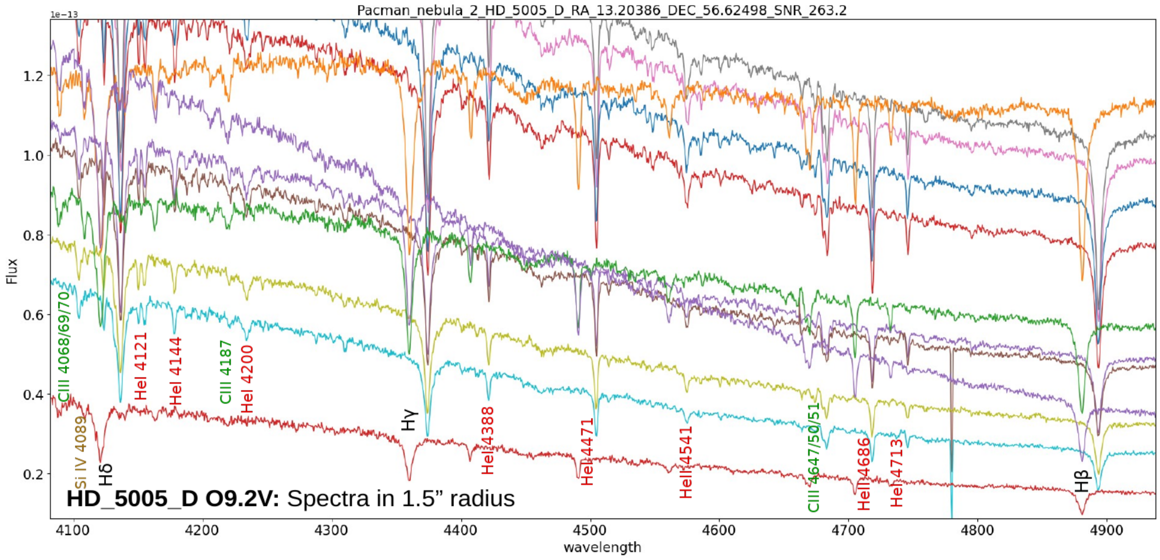

Figure 3: Different spectra for HD 5005 D star, with some of the main lines of the ions used for spectral classification highlighted. The wavelengths of the spectra have not been shifted to the rest position, which is why the lines do not appear at their expected wavelengths.

the relevant lines that facilitate spectral classification, and these lines are of good quality and readily available. This will allow us to carry out the spectral classification effectively. Additionally, since this star is binary, we can observe the displacement on several lines, which will be enable us to study radial velocity as well. Therefore, we confirm that both spectral classification and radial velocity analysis are achievable for our intentions.

4 Future work

We will use these results to advance the MONOS project by classifying binaries and determining orbits. Future work will focus on radial velocities, binarity fractions, and refining orbits with multi-epoch photometry data coming from TESS, Gaia, and including MUDEHaR ([11, 12, 3]).

This program have three ancillary objectives: First, it will contribute to the Villafranca project by confirming cluster memberships, as some clusters are already in the catalog while others will be added later ([9, 11]). Second, the CollDIBs project ([7]) will use LR mode data to extract equivalent widths of broad DIBs from OB-star spectra and HR mode data for narrow DIBs. Lastly, we will derive gas extinction from hydrogen ratios (see [8] for example) in fibers without stars and compare it to stellar extinction. Preliminary results from the Pacman Nebula, featuring four O stars Fig. 4, present already the line flux, line continuum, and a MUDEHaR image of the region.

After analyzing the results from the first two campaigns and utilizing the available LIFU

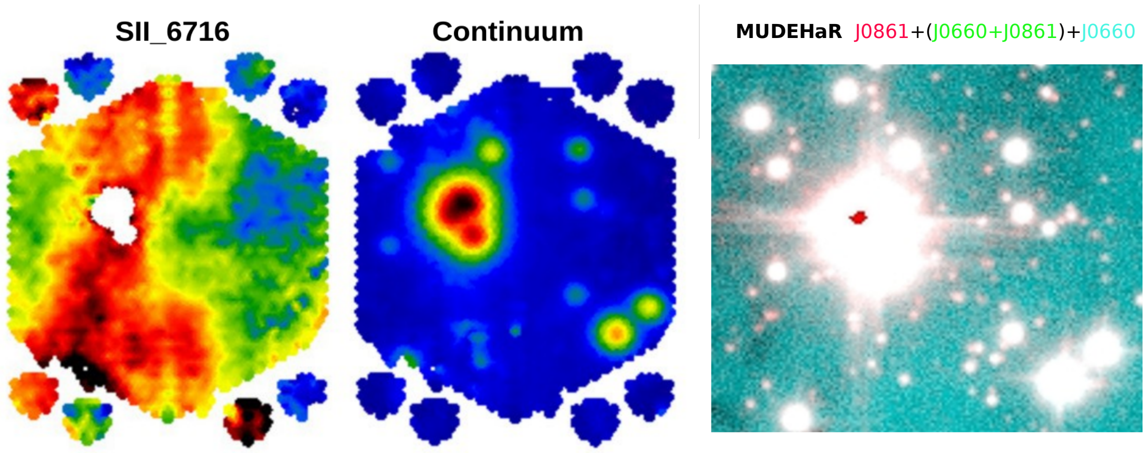

Figure 4: (Left) [S II] 6716 line flux image of the Pacman nebula using a linear intensity scale and blocking the brightest stars. (Middle) Continuum map of the same region using a logarithmic intensity scale. (Right) Image of the region using the MUDEHaR filter combination.

time at WEAVE, we have launched a new observation campaign, our third. This campaign aims to observe an even larger sample of clusters containing massive stars and to conduct detailed analyses within the Villafranca project using line ratios and studying extinction. Our findings from the initial campaigns have demonstrated that this type of analysis is feasible with the data we have collected.

After analyzing the results from the first two campaigns and utilizing the available LIFU time at WEAVE, we have launched a new observation campaign, our third. This campaign aims to observe an even larger sample of clusters containing massive stars and to conduct detailed analyses within the Villafranca project using line ratios and studying extinction. Our findings from the initial campaigns have demonstrated that, unlike MOS observations, LIFU is capable of grouping the fibers and make this type of analysis feasible with the data collected.

Acknowledgments

G.H. acknowledges support from the State Research Agency (AEI) of the Spanish Ministry of Science and Innovation (MICIN) and the European Regional Development Fund, FEDER under grants with references PID2021-122397NB-C21 / PID2022-136640NB-C22 / 10.13039/501100011033.

Based on observations made with the William Herschel Telescope operated on the island of La Palma by the Isaac Newton Group of Telescopes in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias (WEAVE proposal(s) WS2023B2-004, WS2024A2-007, WS2024B2-011, WS2024B2-012).

It used observations made with the JAST/T80 telescope/s at the Observatorio Astrofísico de Javalambre, in Teruel, owned, managed and operated by the Centro de Estudios de Física del Cosmos de Aragón. The initial part of the reduction and astrometric calibration was done by the OAJ Data Processing and Archiving Unit (UPAD) and the main part of the reduction and calibration was done at the Centro de Astrobiología.

References

[1] Elmegreen, B. G. & Lada, C. J. 1977, apj, 214, 725.

[2] Herbig, G. H. 1962, apj, 135, 736.

[3] Holgado, G., Maíz Apellániz, J., Caballero, J. A., et al. 2024, EAS2024, 124

[4] Kudritzki, R.-P. & Puls, J. 2000, araa, 38, 613.

[5] Lada, C. J. & Lada, E. A. 2003, araa, 41, 57.

[6] Maíz Apellániz, J., Sota, A., Morrell, N. I., et al. 2013, Massive Stars: From alpha to Omega, 198.

[7] Maíz Apellániz, J. 2015, memsai, 86, 553.

[8] Maíz Apellániz, J. & Barbá, R. H. 2018, aap, 613, A9.

[9] Maíz Apellániz, J., Crespo Bellido, P., Barbá, R. H., et al. 2020, aap, 643, A138.

[10] Maíz Apellániz, J., Trigueros Páez, E., Negueruela, I., et al. 2020, aap, 639, C1.

[11] Maíz Apellániz, J., Barbá, R. H., Fernández Aranda, R., et al. 2022, aap, 657, A131.

[12] Maíz Apellániz, J., Holgado, G., Pantaleoni González, M., et al. 2023, aap, 677, A137.

[13] Pantaleoni González, M., Maíz Apellániz, J., Barbá, R. H., et al. 2021, mnras, 504, 2968.

[14] Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444.

[15] Trigueros Páez, E., Barbá, R. H., Negueruela, I., et al. 2021, aap, 655, A4.