S-PLUS: An atlas of integrated Hα + [N II] fluxes for planetary nebulae in the Magellanic Clouds

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Resumen / Presentamos un atlas de flujos integrados de Hα + [N II] para nebulosas planetarias de las Nubes de Magallanes (MC PNe) con mediciones del Southern Photometric Local Universe Survey (S-PLUS), una encuesta de imágenes de 12 bandas (7 estrechas y 5 anchas) que nos permite realizar un análisis espacial de la emisión de Hα. Se realizó fotometría de apertura en las imágenes con el continuo sustraído para extraer los flujos de Hα + [N II] de las MC PNe observadas por S-PLUS, enfatizando la fiabilidad del método a través de comparaciones espectroscópicas-fotométricas. Las representaciones visuales demostraron la fidelidad de los datos de S-PLUS en la captura de características espectrales. El trabajo en curso aborda refinamientos en las técnicas de análisis y aplicaciones más amplias de estos mapas de flujo para cálculos de distancia y temperatura.

Abstract / We present an atlas of integrated Hα + [N II] fluxes for planetary nebulae of the Magellanic Clouds (MC PNe) with measurements from the Southern Photometric Local Universe Survey (S-PLUS), a 12-band (7 narrow and 5 broad) imaging survey that allows us to perform a spatial analysis of the Hα emission. Aperture photometry on the continuum-subtracted images was performed to extract Hα + [N II] fluxes of the MC PNe observed by S-PLUS, emphasizing method reliability through spectroscopic-photometric comparisons. Visual representations showcased S-PLUS data fidelity in capturing spectral features. Ongoing work addresses refinements in analysis techniques and broader applications of these flux maps for distance and temperature calculations.

Keywords / planetary nebulae: general — ISM: lines and bands — surveys

1. Introducción

The exploration of Planetary Nebulae (PNe) in the Magellanic Clouds has been ongoing for half a century, experiencing a revitalized focus in the last five years. This renewed interest can be credited to the emergence of new discovery surveys, comprehensive spectroscopic investigations, and a deeper understanding of the Magellanic Clouds themselves. These advancements have notably enriched our understanding of PNe within these celestial systems.

Studying PNe in the Magellanic Clouds offers distinct advantages compared to studies of Galactic PN populations, as outlined by Jacoby & De Marco (2002) and Shaw et al. (2006). Chief among these advantages is the known distance of these systems, facilitating detailed studies of large numbers of PNe and accurate determination of important physical parameters such as sizes and luminosities. Additionally, the average foreground extinction in both the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) is low, enabling the acquisition of large, complete, flux-limited samples without severe selection biases present in the Galaxy. Moreover, both systems are among the most massive in the Local Group, with PN populations totaling hundreds of objects, allowing for the study of statistical properties of various subsamples. Consequently, Magellanic Cloud PNe have been successfully employed over the past few decades to investigate numerous astrophysical questions.

The Small Magellanic Cloud (SMC) is a gas-rich late-type dwarf galaxy (Bolatto et al., 2007) with a gas-to-dust ratio 30 times higher than the Milky Way (Stanimirovic et al., 2000). It is one of the closest and most prominent neighbors of the Milky Way, characterized by its low mass ($M_{\rm dyn} \sim 2.4 \times 10^9 M_\odot$; Stanimirović et al., 2004) and small size ($R_* \sim 3$ kpc). Classified as an irregular galaxy (ImIV−V), the SMC is at a distance of 60.6±3.8 kpc from the Galaxy.

On the other hand, the Large Magellanic Cloud (LMC; Meixner et al., 2006) is a satellite galaxy of the Milky Way and is the fourth-largest galaxy in the Local Group. It is located at a distance of approximately 50 kiloparsecs (Feast, 1999). The LMC is characterized by its irregular shape and prominent bar feature. It contains a rich population of various astrophysical objects, including star clusters, supernova remnants, and, notably, planetary nebulae (Elson et al., 1987; Chu et al., 1993; Leisy & Dennefeld, 1996).

There are two surveys currently mapping the sky in a systematic, complementary way, utilizing 5 broad and 7 narrow-band filters, including Hα: the Javalambre Photometric Local Universe Survey (J-PLUS; Cenarro et al., 2019), covering the Northern celestial hemisphere, and the Southern-Photometric Local Universe Survey (S-PLUS; Mendes de Oliveira et al., 2019), covering the

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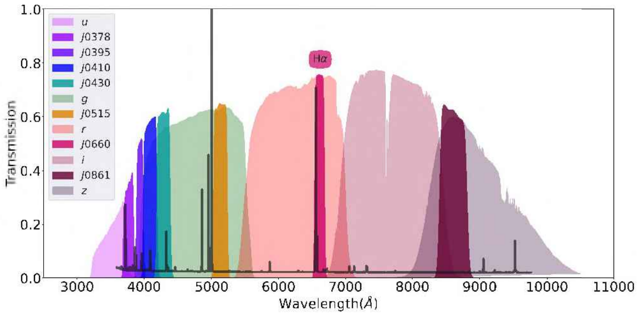

Fig. 1. Transmission curves of the S-PLUS filter set. The narrow-band filter $J0660$ includes the Hα + [N II] emission lines. Over-plotted is a spectrum of typical Galactic PN.

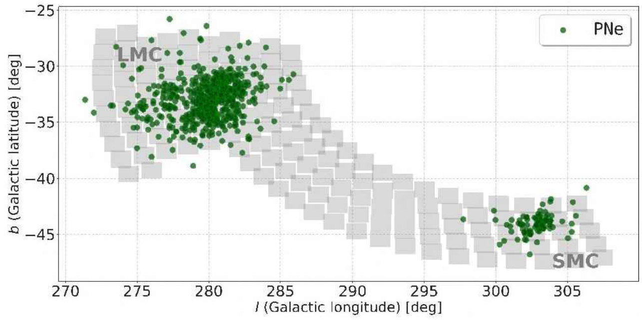

Fig. 2. The distribution of the planetary nebulae from the literature (green circles) in the Magellanic Clouds. The large gray squares indicate the S-PLUS fields that cover both the Large and Small Magellanic Clouds. Almost all the planetary nebulae are within the S-PLUS fields.

southern sky. These two surveys allow leveraging Hα emission lines in the context of PNe (Gutiérrez-Soto et al., 2020).

This study presents an integrated Hα flux atlas for Magellanic Cloud Planetary Nebulae (MC PNe) using S-PLUS imaging and spectroscopy, alongside literature data. Our methodology generated Hα + [N II] flux maps for numerous MC PNe, highlighting method reliability through spectroscopic-photometric comparisons. Visual representations demonstrate S-PLUS data fidelity in capturing spectral features. Ongoing work focuses on refining analysis techniques and exploring broader applications of these flux maps for distance and temperature calculations.

2. Methodology

This manuscript utilizes data from the S-PLUS DR4, covering 3,000 square degrees of the southern sky. S-PLUS DR4 data can be accessed in the `S-PLUS Cloud` database (`https://splus.cloud/`). The survey is conducted by a dedicated 0.83m robotic telescope located at Cerro Tololo, Chile (Mendes de Oliveira et al., 2019).

As shown in Fig. 1, S-PLUS employs the 12 filters from the Javalambre filter system (Marín-Franch et al., 2012), spanning the wavelength range from 3000Å to 10000Å. These include seven narrow-band filters ($J0378$, $J0395$, $J0410$, $J0430$, $J0515$, $J0660$, and $J0861$), and five broad-band Sloan-like filters (Fukugita et al., 1996).

The narrow-band $J0660$ filter used in S-PLUS has a central wavelength of approximately 6614 Å and a width of about 147 Å, covering both the Hα and the doublet [N II] $\lambda\lambda 6548, 6584$ spectral lines (see Fig. 1) for sources up to a redshift of approximately 0.02 (Table 2 of Mendes de Oliveira et al., 2019).

Fig. 2 illustrates the distribution of planetary nebulae in the Magellanic Clouds, showcasing the coverage of S-PLUS fields and the spatial arrangement of these PNe. S-PLUS DR4 comprehensively observes both Magellanic clouds, indicating extensive coverage of PNe in this region. It is worth noting that ∼100 PNe are cataloged in the SMC (Jacoby & De Marco, 2002), while the LMC currently hosts around 700 confirmed PNe (Reid, 2014). Remarkably, more than 95% of these PNe were observed by S-PLUS, indicating that they have corresponding data.

We employed S-PLUS data to derive Hα + [N II] fluxes for PNe in the Magellanic Clouds. This involved extracting fluxes using aperture photometry techniques and generating Hα + [N II] maps from the S-PLUS data. The Hα + [N II] flux for the planetary nebulae in the Magellanic Clouds, observed through the S-PLUS survey, was derived using two broad-band filters (r and i) and one narrow-band filter ($J0660$) as described in Equation 3 by Vilella-Rojo et al. (2015). Hα + [N II] maps were generated using a Python code developed by Lopes et al. (in preparation), based on the technique of Vilella-Rojo. At this stage of the study, we have measured the Hα + [N II] fluxes for the PNe of the SMC, with the next step being the measurement of fluxes for the LMC ones. We have successfully measured the fluxes for 80 SMC PNe.

3. Results

3.1. S-PLUS photometry and VLT/X-shooter spectra

The spectra used in this study were observed with VLT/X-Shooter under Director's Discretionary Time programmes 108.MQ23.001 and 110.23Q7.001, with typical seeing of 0.4 arcsec. Slit widths were 1.3 arcsec, 1.2 arcsec, and 1.2 arcsec for the UVB (300–560 nm), VIS (550–1020 nm), and NIR (1020–2480 nm) arms, respectively, achieving spectral resolutions of $R = 4100$, 6500, and 4300 (Euclid Collaboration et al., 2023). S-PLUS observations for the Main Survey (MS) were conducted with each field observed under photometric conditions and seeing ranging from 0.8 arcsec to 2.0 arcsec per filter. To ensure optimal image quality, the survey avoids nights with seeing conditions worse than 2.0 arcsec (Mendes de Oliveira et al., 2019; Almeida-Fernandes et al., 2022).

Fig. 3 presents a comparison between the VLT/X-shooter spectra and S-PLUS photometry for three Magellanic Cloud planetary nebulae: LHA 115-N 1, SMP SMC 2, and LHA 115-N 70. This comparison highlights the remarkable agreement between the spectroscopic data and photometric observations, showcasing the con-

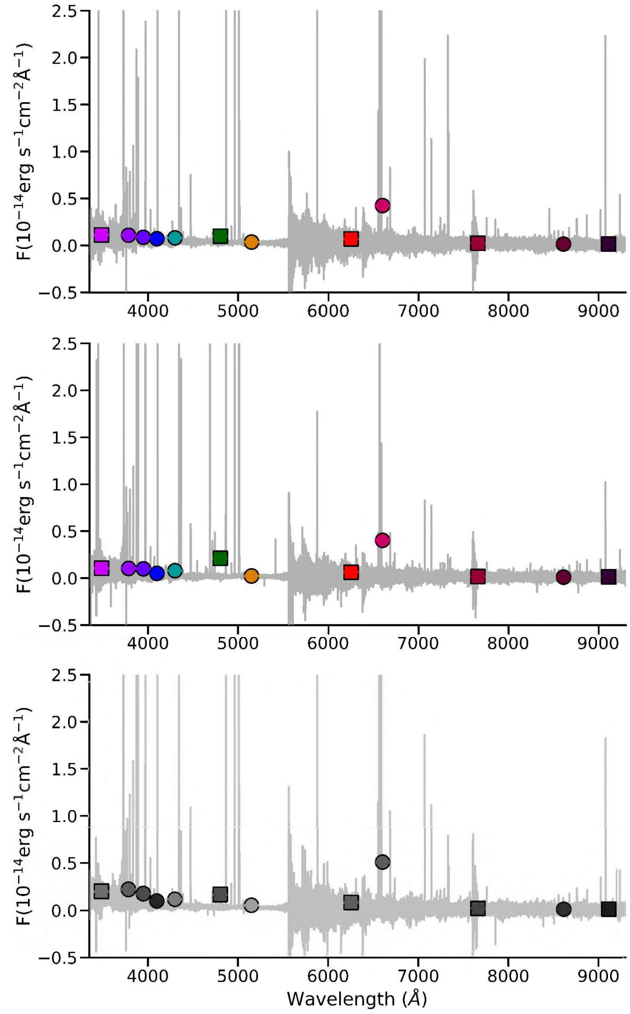

Fig. 3. S-PLUS photometry is represented by the colored points overlaid with VLT/X-shooter spectra of Magellanic Cloud planetary nebulae: (*upper*) LHA 115-N 1, (*middle*) SMP SMC 2, and (*lower*) LHA 115-N 70.

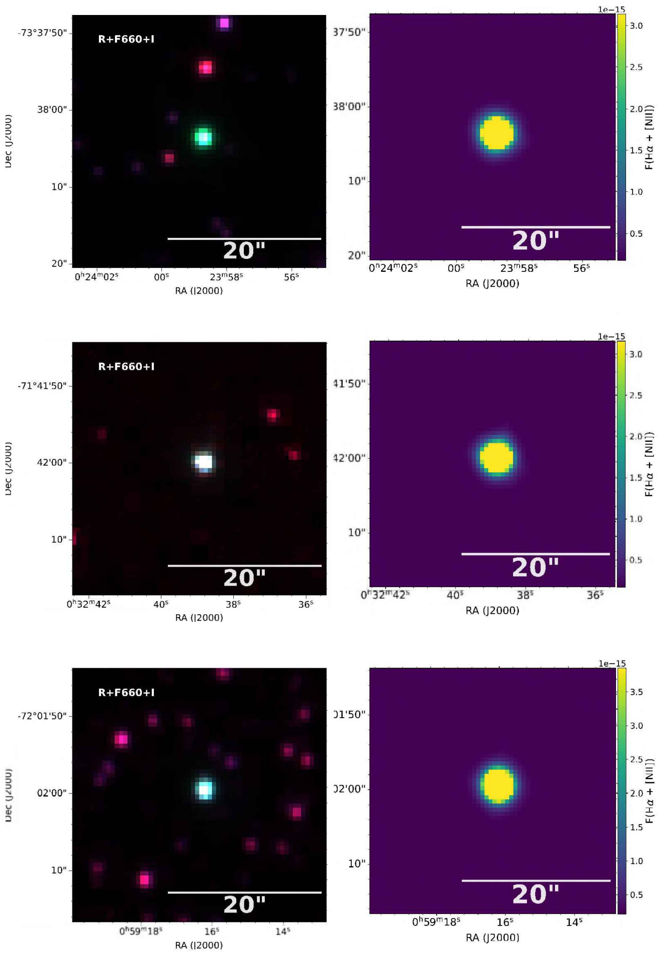

Fig. 4. The *left panel* displays an RGB image composed from r, $J0660$, and i filters, while the *right panel* shows the corresponding Hα + [N II] flux map for the PN shown in Fig. 3, respectively.

sistency and reliability of the S-PLUS data in capturing essential spectral features crucial for planetary nebula characterization. The overlay of colored points representing S-PLUS photometry onto the VLT/X-shooter spectra visually demonstrates this consistency, illustrating the complementary nature of spectroscopic and photometric techniques in astrophysical studies.

Fig. 4 shows the combined RGB image and Hα + [N II] flux maps for three planetary nebulae: LHA 115-N 1, SMP SMC 2, and LHA 115-N 70. Utilizing S-PLUS data, this visualization provides a detailed examination of the spatial distribution of ionized gas within these nebulae. By integrating multi-filter photometry with Hα + [N II] flux mapping, our methodology offers a comprehensive understanding of the emission properties and spatial characteristics of planetary nebulae in the Magellanic Clouds.

3.2. Validating the Hα + [N II] flux maps

To ensure the accuracy of the Hα + [N II] flux maps derived from S-PLUS data, a validation process was undertaken. This process involved the following steps:

- Pseudo Slit Creation:

A pseudo slit was created using the Hα + [N II] map generated from S-PLUS data. This pseudo slit provided a spatially resolved view of the emission line distribution within the PNe. The width of the slit was determined by selecting the region in the Hα + [N II] images that includes pixels with a signal-to-noise ratio larger than 10. We found that a pseudo slit width of 10 pixels was appropriate, given the S-PLUS seeing conditions. With a telescope plate scale of 0.55 arcsec/pixel, the width of the slit corresponds to 5.5 arcsec, which is sufficient to encompass the flux distribution considering the typical seeing of 0.8 to 2.0 arcsec in S-PLUS data and ensuring minimal flux loss.

- Summed Flux:

The flux within the pseudo slit was calculated by summing the flux values along its length. This step allowed for the quantification of the total Hα + [N II]

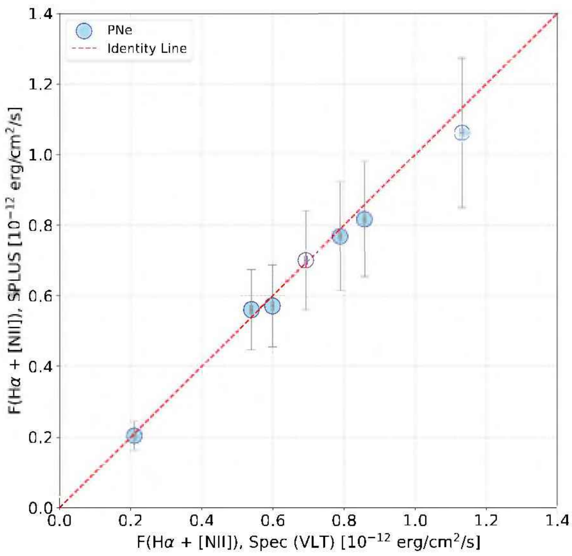

Fig. 5. A comparison between integrated Hα + [N ɪɪ] fluxes obtained from spectroscopy and photometry for seven PNe of the SMC highlights both their consistencies and discrepancies. The error bars on the x-axis are smaller than the symbols. The mean error on the x-axis is around 4.37×10^{-15}.

emission from each PNe.

- Spectroscopic Measurement:

Spectroscopic measurements were conducted to directly capture the Hα and [N ɪɪ] emission lines from the spectra of the PNe. These measurements served as a comparative benchmark for assessing the accuracy of the flux values derived from the Hα and [N ɪɪ] flux maps. By undertaking these validation steps, we ensured the reliability and fidelity of the Hα flux maps generated from S-PLUS data, thus enhancing confidence in the subsequent analyses and interpretations of the emission characteristics of the planetary nebulae. It is worth noting that our validation process initially utilized spectroscopic data from seven VLT/X-shooter spectra. However, we have acquired additional spectra, which will be incorporated into our study to further bolster our findings.

Fig. 5 presents a comparison between integrated Hα + [N ɪɪ] fluxes obtained from spectroscopy and photometry for seven PNe of the Small Magellanic Cloud. Remarkably, the results demonstrate a high level of agreement between the two techniques, highlighting both consistencies and discrepancies. This direct comparison offers valuable insights into potential systematic variations or uncertainties between photometric and spectroscopic measurements, further enhancing our understanding of the emission characteristics of these PNe.

4. Final remarks

In this study, we have demonstrated the effectiveness of combining S-PLUS photometry with spectroscopic analysis to create comprehensive Hα flux maps of PNe in the Magellanic Clouds. Our approach has provided valuable insights into the emission characteristics and spatial distribution of ionized gas within these nebulae. Utilizing spectroscopic data from seven PNe in our study, we have initiated the validation of our methodology. However, our aim is to further strengthen our analysis by incorporating additional spectra, enhancing the robustness of our findings. Additionally, we have applied the methodology developed by Amanda et al. to the PNe observed by S-PLUS in the SMC, ensuring consistency and reliability across our dataset.

Our future work will prioritize measuring Hα + [N ɪɪ] fluxes for PNe in the LMC, while also correcting for [N ɪɪ] and extinction effects in our data. We plan to refine our analysis by incorporating additional spectra and explore further applications of the Hα flux maps. By continuing to refine our methodology and expand our dataset, we aim to deepen our understanding of the physical processes driving the emission properties of planetary nebulae and their implications for stellar evolution.

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References

Almeida-Fernandes F., et al., 2022, MNRAS, 511, 4590
Bolatto A.D., et al., 2007, ApJ, 655, 212
Cenarro A.J., et al., 2019, A&A, 622, A176
Chu Y.H., et al., 1993, ApJ, 414, 213
Elson R.A.W., Fall S.M., Freeman K.C., 1987, ApJ, 323, 54
Euclid Collaboration, et al., 2023, A&A, 674, A172
Feast M., 1999, Y.H. Chu, N. Suntzeff, J. Hesser, D. Bohlender (Eds.), *New Views of the Magellanic Clouds*, vol. 190, 542
Fukugita M., et al., 1996, AJ, 111, 1748
Gutiérrez-Soto L.A., et al., 2020, A&A, 633, A123
Jacoby G.H., De Marco O., 2002, AJ, 123, 269
Leisy P., Dennefeld M., 1996, A&AS, 116, 95
Marín-Franch A., et al., 2012, R. Navarro, C.R. Cunningham, E. Prieto (Eds.), *Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 8450, 84503S
Meixner M., et al., 2006, AJ, 132, 2268
Mendes de Oliveira C., et al., 2019, MNRAS, 489, 241
Reid W.A., 2014, MNRAS, 438, 2642
Shaw R.A., et al., 2006, ApJS, 167, 201
Stanimirović S., Staveley-Smith L., Jones P.A., 2004, ApJ, 604, 176
Stanimirovic S., et al., 2000, MNRAS, 315, 791
Vilella-Rojo G., et al., 2015, A&A, 580, A47