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Hidden jets in planetary nebulae and how to find them

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Almost 80% of the planetary nebulae (PNe) are non-spherical - elliptical, bipolar, point-symmetric, among others - sometimes showing knots, filaments and jets of low ionization (the low-ionization structures, LIS), and others features of small scales. The presence of stellar jets in PNe has been investigated through morpho-kinematic studies, from narrow-band images and position-velocity maps constructed from high-dispersion, long-slit spectroscopic observations. However, this spectroscopic technique limits the understanding of the global three-dimensional structure of the PNe, since the spatial and spectral information are only obtained along a given orientation. Integral field units (IFU) allow the spatial and kinematics mapping of PNe, for both their small- and large-scale components, to determine their morphology, kinematics, density distribution, and the interaction zone of the jets with the surroundings. Many of the stellar jets have only been unveiled through this modern instrumental technique. In this talk, I will present results obtained with the optical IFU MEGARA, which highlight the hidden ways that PNe ejecta return their products to the interstellar medium, in a variety of morphologies. In particular: i) the extension of the extremely faint bipolar jet in NGC 2392, mapped for the first time; ii) the kinematic dissection of the born-again HuBi 1; iii) the multiple structures of the M2–31, and finally iv) the presence of a fast outflow aligned with the symmetry axis of M3-38.

The study aimed to detect hidden jets in four planetary nebulae (PNe) using the IFU MEGARA (High Resolution GTC Multi-Spectrograph for Astronomy, (Gil de Paz et al., 2018)) attached on the Gran Telescopio Canarias (GTC). We used the high-resolution Volume-Phased Holographic (VPH) grism VPH665-HR covering the 6405.6-6797.1 Å wavelength range. The four PNe studied and the results found are the following:

HuBi 1: A PN with a [WC 10] central star, exhibiting an uncommon ionization structure, with the outer shell showing higher ionization compared to the innermost regions (Guerrero et al., 2018). Velocity tomography revealed shell-like structures expanding at $\simeq$ 300 km s^{-1} (Rechy-García et al., 2020).

NGC 2392: This PN has a complex morphology and presents high-velocity bipolar outflows. MEGARA provided the first image of its jets, showing velocities with the approaching component jet is between -190 km s^{-1} to -150 km s^{-1}, and receding from +150 km s^{-1} to +190 km s^{-1} (Guerrero et al., 2021).

M 2-31: A compact PN with a [WC4-6] central star. Five kinematic components were identified with MEGARA (Rechy-García et al., 2021).

M 3-38: This PN has a binary system and a fast collimated outflow with a velocity of 225 km/s. MEGARA observations detected additional high-velocity clumps orthogonal to its bipolar axis (Rechy-García et al., 2022)

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