

# Imaging the elusive H-poor gas in planetary nebulae with large abundance discrepancy factors

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**Abstract.** The discrepancy between abundances computed using optical recombination lines (ORLs) and collisionally excited lines (CELs) is a major, unresolved problem with significant implications for the determination of chemical abundances throughout the Universe. In planetary nebulae (PNe), the most common explanation for the discrepancy is that two different gas phases coexist: a hot component with standard metallicity, and a much colder plasma enhanced in heavy elements. This dual nature is not predicted by mass loss theories, and direct observational support for it is still weak. In this work, we present our recent findings that demonstrate that the largest abundance discrepancies are associated with close binary central stars. OSIRIS-GTC tunable filter imaging of the faint O II ORLs and MUSE-VLT deep 2D spectrophotometry confirm that O II ORL emission is more centrally concentrated than that of [OIII] CELs and, therefore, that the abundance discrepancy may be closely linked to binary evolution.

**Keywords.** binaries: close — ISM: abundances — (ISM:) planetary nebulae: general — stars: winds — stars: outflows

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## 1. Introduction

The abundance discrepancy problem was first discovered in the physics of gaseous nebulae more than 70 years ago (Wyse 1942). It pertains to the fact that chemical abundances obtained from optical recombination lines (ORLs) are systematically larger than those obtained from collisionally excited lines (CELs) of the same ion. Generally, this discrepancy is parameterized by the abundance discrepancy factor (ADF), which for a given ion is defined as the ratio of ionic chemical abundances derived from ORLs and from CELs. Photoionized gaseous nebulae exhibit different ADF values. While H II regions have moderate and nearly constant values ( $ADF \sim 2 - 3$ ; see García-Rojas & Esteban 2007), planetary nebulae (PNe) can reach values as large as 120 (Corradi *et al.* 2015). García-Rojas & Esteban (2007) concluded that the physical origin of the abundance discrepancy in PNe with extreme ADF values should be different to that of H II regions and the bulk of PNe, where moderate values are found.

Regarding PNe, in the last few years our group has focused on the possible link between the large ADFs found in some PNe and the binary nature of their central stars (Corradi *et al.* 2015; Jones *et al.* 2016). We have seen that it is relatively common to

find extremely large ADFs in PNe with binary central stars that have experienced a common-envelope episode (post-CE PNe; e. g. Liu *et al.* 2006), reaching extreme values in the inner regions of several such objects (e. g. in the central  $7''$  of Abell 46,  $\text{ADF} \sim 300$ ). Our recent observations of the large ADF PN NGC 6778 taken with the 10.4m Gran Telescopio Canarias (GTC) show that the spatial distribution of the  $\text{O}^{2+}$  ions producing the O II ORLs does not match that of the  $\text{O}^{2+}$  ions emitting the [O III] CELs; additionally, O II ORL emission is concentrated in the central parts of the nebula (García-Rojas *et al.* 2016). This is consistent with the presence of two distinct plasmas that are not well mixed, perhaps because they were produced in different ejection events. Our results are important because, for the first time, the evolution of close binary stars is clearly linked with the large ADFs in PNe. These results have encouraged us to acquire additional data in order to strengthen the link between the common-envelope process and the abundance discrepancy phenomenon. In particular, we have obtained high spatial resolution 2D spectroscopy with MUSE-VLT and direct imaging with a tunable filter using OSIRIS-GTC to study in detail the spatial distributions of both ORL and CEL emissions.

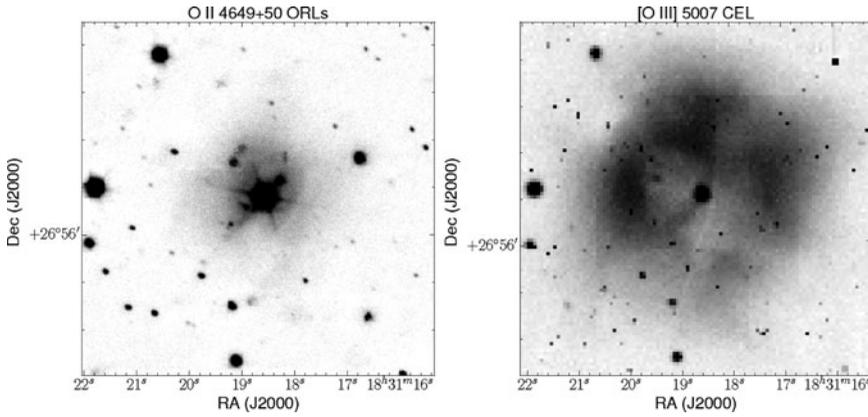
## 2. Observations

*GTC observations.* We obtained narrow-band images of Abell 46 using the blue tunable filter of the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS) instrument at the 10.4m GTC (La Palma) on 20 September 2016. Since the central wavelength of the tunable filter is not constant across the size of Abell 46 ( $\sim 70''$  diameter), a two-step scanning was required, centered at 4652 and 4656 Å, respectively. We took 7 exposures of 1900 s in each configuration to reach the signal-to-noise ratio needed to detect the emission from the faint O II ORLs. For details of the observing and reduction technique, see García-Rojas *et al.* (2016).

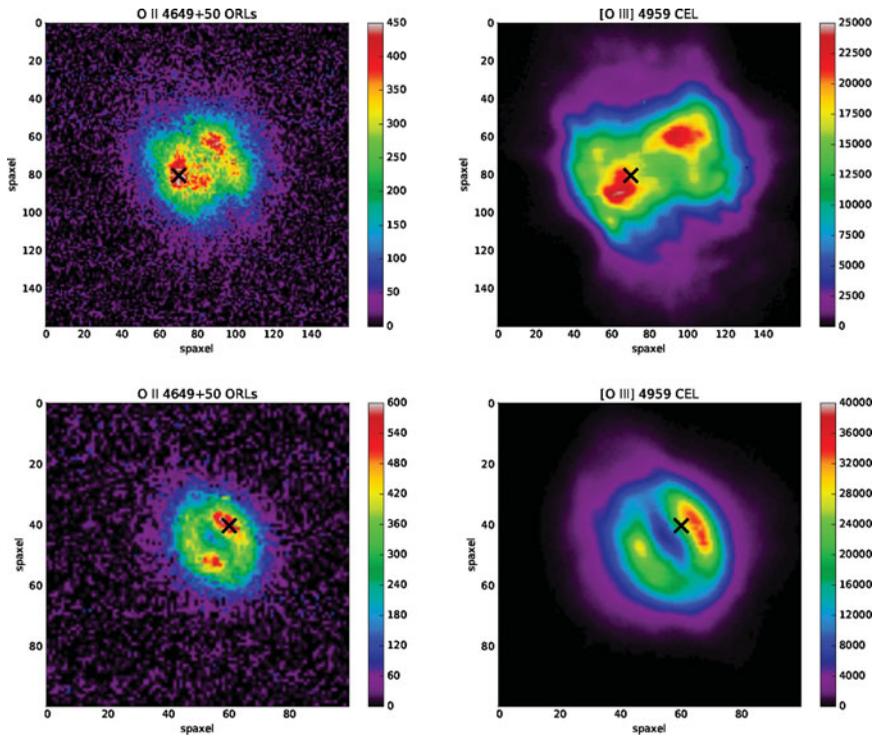
*VLT observations.* Observations were made with the Multi Unit Spectroscopic Explorer (MUSE) mounted on VLT UT4 on 6 July 2016. The extended wide field mode was used, with a field of  $60 \times 60''$ , a 0.2 spaxel size and a wavelength coverage of 4650–9300 Å at a mean spectral resolution of  $\sim 2500$ , enough to isolate the emission of the brightest O II ORLs. We observed 5 large ADF PNe. For each object, we made 5 long exposures (between 150 s and 1800 s, depending on target) to have enough S/N ratio to detect the faint O II ORLs. We applied a dither pattern and a rotation of 90 degrees between the different exposures to avoid bad pixels and to get rid of any MUSE systematics. We also took two sky exposures to remove the sky-background emission from our final spectra. We followed the standard reduction procedures described in Walsh *et al.* (2016) using the instrument pipeline version 1.0 (Weilbacher *et al.* 2014). Each datacube was completely reduced, sky subtracted and wavelength and flux calibrated. Only a single datacube for each object was used in the present work.

## 3. Results

Abell 46 is the PN with the largest ADF ever measured in an integrated spectrum of a PN ( $\sim 120$ ; see Corradi *et al.* 2015), and has been shown to harbor a post-common-envelope central binary star (Afsar & Ibanoglu 2008). In Fig. 1 we show the spatial distribution of the O II  $\lambda\lambda 4649+50$  ORLs emission (left), compared to that of the [O III]  $\lambda 5007$  CEL (right). Similar to what was observed in NGC 6778 by García-Rojas *et al.* (2016) using the same technique, the emission of ORLs is clearly produced closer to the binary central star than the CEL emission. This is consistent with the results of



**Figure 1.** OSIRIS-GTC tunable filter image of Abell 46 in the O II 4649+50 ORLs (left), compared with an image taken with the 3.6m NTT in the [O III] 5007 CEL (right).



**Figure 2.** Preliminary maps of the O II  $\lambda\lambda 4649+50$  ORLs (left panels) and of the [O III]  $\lambda 4959$  CEL for two PNe in our sample: NGC 6778 (ADF $\sim$ 20; top panels), and M 1-42 (ADF $\sim$ 20; bottom panels). It is worth re-emphasising that the O II and the [O III] emission comes from the same ion: O<sup>2+</sup>. The “x” marks a reference spaxel.

Corradi *et al.* (2015) for Abell 46, who analyze the emission spatial profiles with long-slit spectroscopy (see their Figure 4).

In Fig. 2 we show the continuum subtracted MUSE-VLT maps of the O II  $\lambda\lambda 4649+50$  ORLs (left panels) and of the [O III]  $\lambda 4959$  CEL (right panels) for NGC 6778 and M 1-42. It is clear that in both objects the emission of ORLs is more centrally concentrated than the emission of the strongest [O III]  $\lambda 4959$  CEL. Both PNe have very similar ADFs of

$\sim 20$  (see Jones *et al.* 2016 and McNabb *et al.* 2016). NGC 6778 has a close binary central star that has undergone a common envelope phase (Miszalski *et al.* 2011). However, the central star of M1–42 has not been reported as binary, although its asymmetric morphology, large ADF and the behaviour found in this work suggests that it is an excellent candidate to search for binarity.

We observed three additional objects. Hf2–2, a PN with one of the largest known ADFs ( $\sim 80$ ; McNabb *et al.* 2016), is known to host a close binary central star (Hillwig *et al.* 2016). NGC 6153 and NGC 7009 are very bright and well-studied PNe with relatively large ADFs ( $\sim 10$ ) but without known central binary stars (Liu *et al.* 2000; Fang & Liu 2013). For Hf2–2 there is also clear evidence of a more centrally concentrated emission of O II ORLs relative to the emission of [O III] CELs. However, given the brightness of NGC 6153 and NGC 7009 and the relatively low S/N of O II ORLs with respect to the continuum, a very careful continuum subtraction must be performed to clearly see the different spatial distributions of the O II and [O III] emission.

Our observations have added a new, unexpected ingredient to understand the abundance discrepancy problem: large ADFs should be explained in the framework of close-binary evolution. A reasonable explanation related to binary evolution (nova ejecta, the presence of the common-envelope remnant or disk, etc.) should be invoked to explain the observed behavior.

#### 4. Acknowledgements

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#### Discussion

LIU: Liu *et al.* (2000; Figs. 17, 18) show that ORLs are more peaked towards nebular centre (i.e. higher ADFs). This is in contrast with your new MUSE imaging observation.

GARCÍA-ROJAS: You are right. In fact I was surprised about these results in NGC6153. However, these are preliminary results and a more detailed continuum subtraction should be done for the brightest objects, as the large exposure times make continuum subtraction difficult because continuum is very strong in the O II ORL zone.

BALICK: If ORLs arise closer to the nuclei than CELs, then those PNe with large central cavities should show relatively weak ORLs and lower ADFs. Have you corrected ADFs with nebular morphologies?

GARCÍA-ROJAS: We have not tried what you proposed, but we will explore your suggestion. Thanks.