Abstract. A number of planetary nebulae show binary central stars and significant abundance discrepancies between values estimated from collisionally excited lines when compared to the same abundances estimated from recombination lines. One approach to investigate this yet unsolved problem is using spatially resolved images of emission lines in an attempt to detect a possibly distinct metal rich component in the nebula. In this work we present results of spatially resolved abundance analysis of NGC 6778 based on data gathered from VLT VIMOS-IFU. We discuss the spatial variations found as well as possible limitations of the method in answering questions about abundance variations.

1. Introduction

Chemical abundances in planetary nebulae are important as a tool to study stellar evolution, estimate effects of internal stellar nucleosynthesis and mixing, among others issues related to chemical evolution. Because of that PNe are used to study the chemical evolution in the Galaxy and in other nearby galaxies. It is well known (see e.g. Osterbrock & Ferland 2006) that in photoionized nebulae – both H II regions and planetary nebulae – optical recombination lines (ORLs) provide chemical abundance values that are systematically larger than those obtained using collisionally excited lines (CELs). The abundance discrepancy factor (adf) between ORLs and CELs is usually between 1.5 and 3 (see e.g. García–Rojas & Esteban 2007, Liu 2012), but in planetary nebulae (PNe) it has a significant tail extending to much larger values. This is generally known as the abundance discrepancy problem. It has been around for more than seventy years (Wyse 1942), and is one of the major unresolved problems in nebular astrophysics. The problem has far-reaching consequences on the measurement of abundances throughout the Universe, as the chemical content of near and far-away galaxies is most often done using CELs from their ionized gas (e.g. Hamann et al. 2002).
Corradi et al. (2015) have recently shown that the largest abundance discrepancies are reached in planetary nebulae with close binary central stars. For instance, in the PNe Abell 46, Ou5, and NGC 6778, which have binary central stars with orbital periods of a few hours, they found $O^{2+}/H^+$ ads larger than 40, and as high as 300 in the inner regions of Abell 46. Spectroscopic analysis supports the previous interpretation that two different gas phases coexist in these nebulae (e.g. Liu et al. 2006, Tsamis et al. 2008): hot gas at $10^4$ K with standard metallicity where the CELs can be efficiently excited, and a much cooler ($10^3$ K) plasma with a highly enhanced content of heavy elements (which is likely the cause of the cooling) where only ORLs form. How much each gas component contributes to the total mass, and how they are distributed and mixed, is basically unknown. In this work we show the results for the object NGC 6778 obtained from VLT IFU data and spatially resolved abundance analysis. The present effort is part of a larger project that aims to understand the large discrepancy in PNe.

2. Observational data

The observations were obtained with the instrument VIMOS-IFU, attached to ESO-VLT-U3 on the 14 of september, 2007. The instrument is composed of 6400 fibers and, has a changeable scale on the sky that was set to 0.33” per fiber, to obtain our data. The image is formed by a matrix of 40x40 fibers, which gave us a coverage of 13.2"x13.2” on the sky. We obtained observations in high-resolution mode, with a pixel scale of 0.6 Å pix$^{-1}$ with a useable range from 3900 Å to 7000 Å, considering both the blue and red grisms of the spectrograph. The object was observed with an exposure time of 300 seconds in both red and blue configurations. The reduction was performed with the VIMOS pipelines available at the instrument website\footnote{\url{http://www.eso.org/sci/facilities/paranal/instruments/vimos/}}.

3. Results

In Fig.\footnote{\url{http://www.eso.org/sci/facilities/paranal/instruments/vimos/}} we show the emission-line maps for some of the most important lines we detected, which were also used to obtain diagnostics of the electron densities and temperatures. Because we do not deal with integrated fluxes, the typical signal-to-noise ratio in a volumetric pixel (voxel) of the data cube can be significantly lower in comparison to usual long-slit data. In practice, the trade-off of spatial resolution is lower signal to noise ratio (S/N) in a given pixel of the observed map. The limited S/N may result in significant noise when spatially resolved diagnostic ratio maps are computed. To improve the quality of the final maps we applied a median noise filter to remove some of the noise, especially in the low S/N regions. To work with the emission line maps presented in Fig.\footnote{\url{http://www.eso.org/sci/facilities/paranal/instruments/vimos/}} and derive the nebular properties (internal extinction, electron densities, and temperatures and abundances), we used a set of Python scripts and the NEAT software described in detail in Wesson et al. (2012).
The code computes the extinction coefficient $c(H\beta)$ using the available Balmer lines. The extinction-corrected emission-line maps were used to derive the spatial distribution of the electron density ($N_e$) and temperature ($T_e$) of the nebula as well as abundances and abundance discrepancy factors (ADFs). For the calculations we adopted the extinction law of Howarth (1983). The atomic data used for He I abundances is from Smits (1996). The ICF scheme used to correct for unseen ions was that of Delgado-Inglada et al. (2014). The results for the physical and chemical properties are shown in Figs 4. through 8. The results obtained here corroborate previous results from long-slit spectra presented by Jones et al. (2016) and expand on the ones from García-Rojas et al. (2016).

![Figure 1](image1.png)

Figure 1. Temperature (upper left), abundances obtained from CELs (upper right), both with the [OIII]4363 contours overlaid, from RELs (lower left) and ADF maps (lower right with the OII 4650 contours overlaid) for NGC 6778.

4. Conclusion

The planetary nebula NGC 6778 has been studied with data from the VLT IFU instrument from where we collected high resolution spatially resolved spectra. The nebula shows a density enhanced waist which correlates with the bright emissions regions seen in both [SII] and [NII] lines. The temperature estimated
from the low ionization [NII] lines as well as the [OIII] lines, shows hotter regions along the axis perpendicular to the main waist. The abundance maps also show structural variations that seem to follow the axis perpendicular to the main waist. Interestingly the abundance variations obtained from recombination lines show an increase towards the central region of the nebula while the abundances obtained from collisional lines show increases that are coincident with the higher density waist. The [OIII]4363 emission resembles the OII recombination emission but not the strong [OIII]5007 emission which may be due to presence of a high-density, H-poor gas component in the inner regions of the nebula. The H-poor component could be the source of the OII emission and the cause of the abundance discrepancy. The ADF maps show larger discrepancies correlated with the axis perpendicular to the waist, consistent with values obtained by Jones et al. (2016). These results may provide important constraints for the existence and formation times of jets (Guerrero & Miranda, 2012). All this information will also help in constraining the role of binaries and their relation to the geometry and ejection mechanism of the metal rich (H-poor) component.

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