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The shape of the ionised gas abundance distribution in spiral galaxies.

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Abstract

In this contribution we review some of the most relevant results of the PhD thesis awarded with the XIV SEA PhD prize in 2018. The thesis is aimed at characterising the ionised gas abundance distribution in spiral galaxies by using two sets of high-quality integral field spectroscopic data from the CALIFA and AMUSING surveys. We observe that, together with the well-known radial negative gradient, a significant number of galaxies also display a drop in the abundances towards the inner parts of the discs and a flattening in the outermost regions. This suggests that the widely accepted scenario in which the oxygen abundance distribution of spiral galaxies is well described by a single radial negative gradient might be incomplete and deviations from it are needed for a proper characterisation of the distribution. In addition, in the particular case of the galaxy NGC 6754, we perform an analysis of its azimuthal abundance and velocity-residual distributions. This galaxy shows, for the first time, clear signatures of ongoing gas radial migration affecting the abundance distribution. The results obtained in this thesis provide strong constraints to chemical evolution models aimed at explaining the formation and evolution of spiral galaxies, trying to do our bit in the comprehension of the Universe around us.

1 Introduction

The thesis, entitled "The shape of the ionised gas abundance distribution in spiral galaxies", was conducted by Laura Sánchez Menguiano in the Instituto de Astrofísica de Andalucía (IAA-CSIC) under the supervision of Sebastián Sánchez and Isabel Pérez. In the context of the formation and evolution of spiral galaxies, the study of their gas-phase chemical composition has proven to be a powerful tool to improve our knowledge on the evolution of these complex systems. In particular, the analysis of H II regions (regions of ionised gas associated with star formation) is of great importance, as it is through the birth and death of stars that the galaxies chemically evolve.

In this thesis we use two sets of high-quality integral field spectroscopic (IFS) data from two different surveys, CALIFA [28] and AMUSING [9], to characterise the oxygen abundance distribution of the ionised gas in star-forming (SF) regions of spiral galaxies. The first survey provides a sample of 122 disc galaxies extracted from a well-defined, statistically significant mother sample, representative of galaxies in the Local Universe. The latter provides a sample of 102 galaxies that allows us to complement the study based on CALIFA data using a higher spatial resolution dataset.

The abundance distribution of the analysed galaxies is determined based on the calibration proposed by [16] for the O3N2 strong-line indicator (although others are also tested showing that all the qualitative results derived from this study are not contingent upon the choice of the used calibrator). To measure the emission lines involved we apply FIT3D-Pipe3D [30], an extensively tested code designed to deal with spatially resolved IFS data (see [32, 33]).

The study of the 2-dimensional (2D) ionised gas abundance distribution is addressed by analysing separately the radial and azimuthal trends. The large number of SF regions provided by both analysed samples, together with the good coverage of the galaxy discs with high spatial resolution, allow us to undertake this study as never done before. In the following sections we will present the main results of each of these analyses and the conclusions resulting from our work.

2 Radial oxygen abundance distribution

The radial distribution of the chemical abundances in disc galaxies has been studied for decades, being nowadays unquestionable that spiral galaxies exhibit in general a negative trend in metallicity. This was firstly proposed in the 1970s [38, 39, 40, 25], and since then, an extensive body of literature has been amassed on the subject of abundance gradients in nearby galaxies supporting these negative trends [42, 41, 24, 31, 29, 12, 2].

However, gas metallicity studies have also presented some hints of the existence of some behaviours in the oxygen abundance profiles that deviate from the pure radial decline: A decrease or a nearly flat distribution of the abundance in the innermost region of discs (e.g. [3, 27, 29]); and a flattening in the gradient in the outer regions measured in several works ([18, 43, 41, 27, 31, 46], among others). Despite the wide variety of mechanisms proposed to explain the presence of these features (such as radial migration, [21, 22]; or satellite accretion, [26, 4]), its origin is still unclear.

However, most of the previously mentioned studies were limited by statistics, either in the number of observed H II regions, their coverage across the galaxy surface or the size of the analysed sample of galaxies. The study of the radial oxygen abundance distribution carried out in this thesis is first performed in a spaxel-by-spaxel basis using the CALIFA sample (122 galaxies), taking advantage of the full 2D information to properly map the abundance distribution. This type of analysis is feasible because the spaxel size of CALIFA

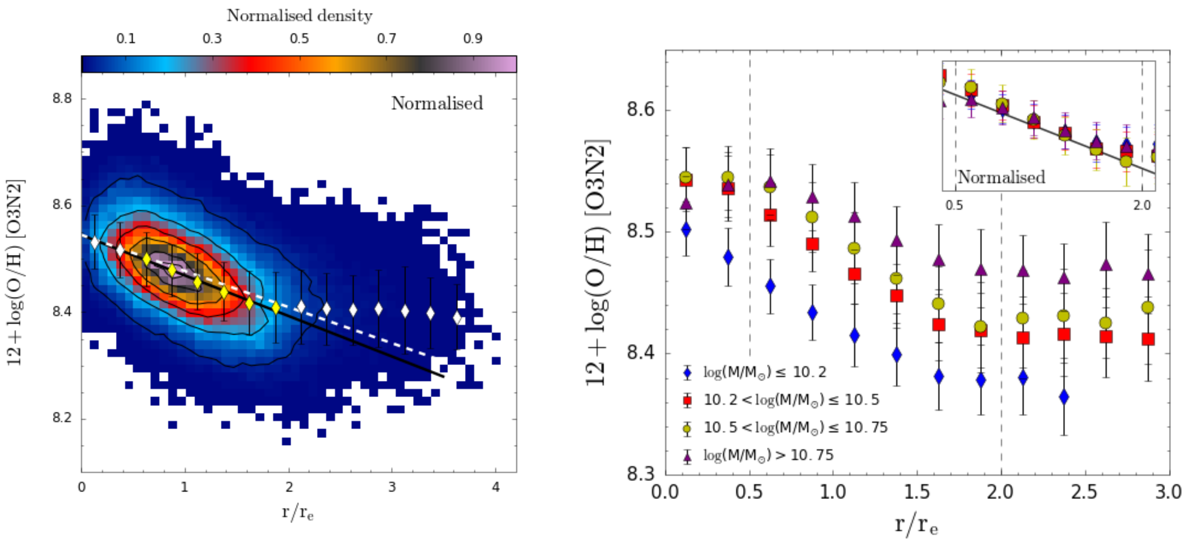

Figure 1: *Left*: Normalised radial density distribution of the oxygen abundance in the CALIFA sample, where the presence of a common gradient between 0.5 and 2.0 r_e and an outer flattening beyond 2.0 r_e are observed. *Right:* Average oxygen abundance radial profiles for galaxies divided in four different mass bins, where it is visible the existence of an inner abundance drop and its dependency with the galaxy mass.

datacubes is of the order of the size of an H II region and prevents us to resolve its ionised structure. With this premise, we also analyse the oxygen abundances derived for individual H II regions for comparison purposes, obtaining equivalent results with both procedures. In addition to the general negative gradient displayed by the galaxies, an inner drop and/or outer flattening are observed in the oxygen abundance radial profile (see Fig. 1). Concerning the negative trend, we find that there is a common abundance gradient between 0.5 and 2.0 r_e of $\alpha_{O/H} = -0.075 \pm 0.016\,\mathrm{dex/r_e}$ when normalising the distances to the disc effective radius. By performing a set of KS tests, we determined that this slope is independent of other galaxy properties, such as morphology, absolute magnitude, and the presence or absence of bars. In particular, barred galaxies do not seem to display shallower gradients, as predicted by numerical simulations and reported by early studies (e.g. [45]). Interestingly, we find that a high number of galaxies with reliable oxygen abundance values beyond two effective radii (57) present a flattening of the abundance gradient in these outer regions. This flattening is not associated with any morphological feature, which suggests that it is a common property of disc galaxies. Finally, we detect a drop or truncation of the abundance in the inner regions of 27 galaxies in the sample; this is only visible for the most massive galaxies. For more details of this analysis performed with CALIFA data we refer the reader to [35].

The high spatial resolution provided by AMUSING data allows us to improve the study on the radial oxygen abundance distribution. This dataset helps us to increase the number of H II regions detected in individual galaxies with respect to previous studies. In addition, we can avoid the dilution effects and reduce the contamination of the diffuse emission in the

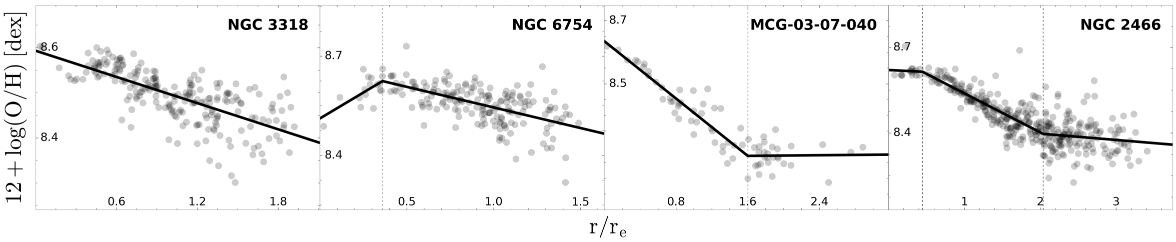

Figure 2: Examples of the different shapes found in the oxygen abundance radial distribution of the H II regions. The solid black line represents the fit to the distribution and the dashed vertical lines correspond to the radial position of the inner drop and/or outer flattening.

detected regions, effects that affected the spaxel-by-spaxel analysis with CALIFA. In this analysis we develop a new methodology to automatically fit the abundance radial profiles (see Fig. 2), finding that 55 galaxies of the sample exhibit a single negative gradient. The remaining 47 galaxies also display, as well as this negative trend, either an inner drop in the abundances (21), an outer flattening (10), or both (16), which suggests that these features are a common property of disc galaxies. We confirm the results found with CALIFA: the presence and depth of the inner drop depends on the stellar mass of the galaxies with the most massive systems presenting the deepest abundance drops, while there is no such dependence in the case of the outer flattening (see Fig. 3). As opposite to the previous study, where the radial position of these features was deduced based on visual inspections of the general shape of the gradient, in this analysis the developed methodology allowed us to determine automatically their actual location. We find that the inner drop appears always around $0.5\,\mathrm{r_e}$, while the position of the outer flattening varies over a wide range of galactocentric distances. Regarding the main negative gradient, we find a characteristic slope in the sample of $\alpha_{O/H} = -0.10 \pm 0.03\,\mathrm{dex/r_e}$ (compatible with the value recovered from the CALIFA data, see Fig. 3). This slope is independent of the presence of bars and the density of the environment. However, when inner drops or outer flattenings are detected, slightly steeper gradients are observed. This suggests that radial motions might play an important role in shaping the abundance profiles. Besides, we define a new normalisation scale ('the abundance scalelength', $r_{O/H}$) for the radial profiles based on the characteristic abundance gradient, with which all the galaxies show a similar position for the inner drop ($\sim 0.5\,r_{O/H}$) and the outer flattening ($\sim 1.5\,r_{O/H}$). Finally, an analysis of the dispersion around the negative gradient arises no significant dependence with any property of the galaxies, with values compatible with the uncertainties associated with the derivation of the abundances. A more detailed explanation of this analysis with AMUSING data can be found in [37].

3 Arm and interarm abundance gradients

Spiral arms are one of the most distinctive features in disc galaxies. These structures can exhibit different patterns, namely grand design and flocculent arms, with easily distinguishable

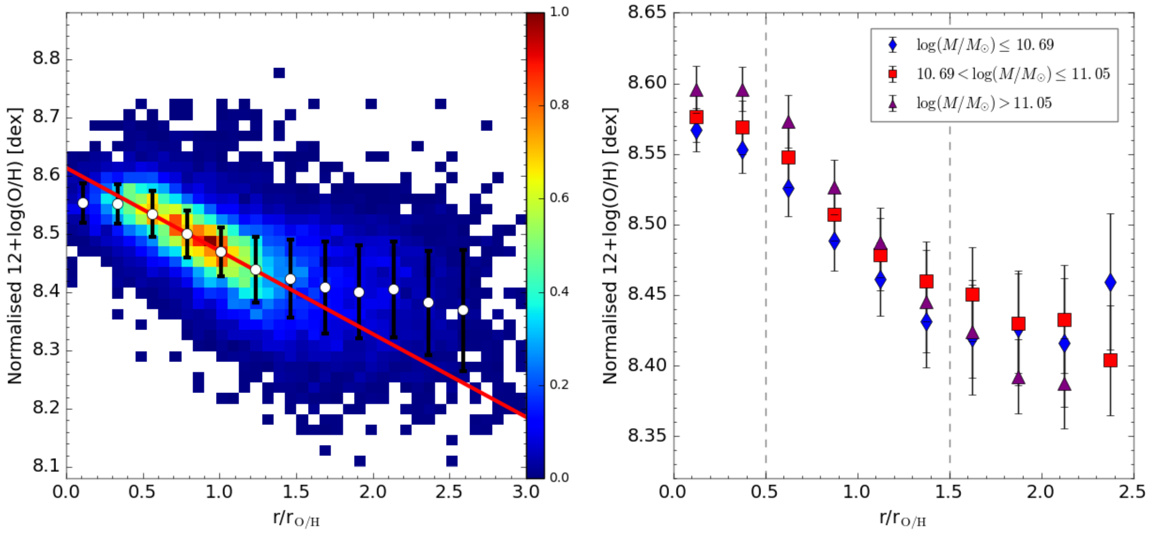

Figure 3: Same as Fig. 1 but for the AMUSING sample and normalising the galactocentric distances to the new defined normalisation scale $r_{O/H}$ ('the abundance scalelength'). See text for more details.

characteristics (long, symmetric, and continuous arms in the former case, small and patchy in the latter). However, their origin and the mechanisms shaping them are unclear. The overall role of spirals in the chemical evolution of disc galaxies is another unsolved question. In particular, it has not been fully explored if the H II regions of spiral arms present different properties from those located in the interarm regions. Very few works have focused on this study, all of them based on small sample of galaxies and not finding evidences of chemical differences between arm and interarm regions [19, 7].

In this thesis we also study the radial oxygen abundance gradient of the arm and interarm SF regions of a subsample of 63 galaxies using CALIFA data. We focus the analysis on three characteristic parameters of the profile: slope, zero-point, and scatter. The sample was morphologically separated into flocculent versus grand design spirals and barred versus unbarred galaxies. We find subtle but statistically significant differences between the arm and interarm distributions for flocculent galaxies, while no significant differences are found for grand design systems. In addition, we find an increase in the scatter when moving away from the spiral arms for flocculent galaxies, whereas grand designs present a similar scatter within the interarm region (see Fig. 4). All this suggests that the mechanisms generating the spiral structure in both type of galaxies may be different. Grand design arms would be linked to quasi-stationary density waves, which move across the disc affecting the gas content of the entire galaxy and diluting possible differences between the arm and interarm regions. On the other hand, flocculent arms would be associated with transient local density instabilities, that affect always the same material (SF regions in the arms), increasing the differences between the arm and the interarm regions. Another possibility is that these differences may be due to a higher star formation *outside* the spiral arms for the flocculent galaxies and a

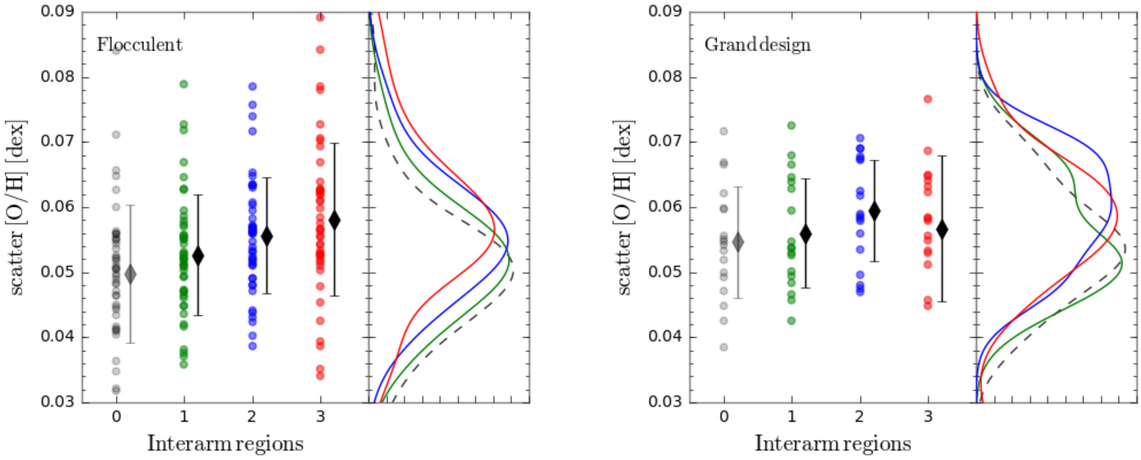

Figure 4: Distribution of the scatter of the oxygen abundances in the interarm regions according to the angular distance to the spiral arms (labeled as region 0) for flocculent (*left panel*) and grand design (*right panel*) galaxies. Each point represents the scatter of the SF spaxels within the corresponding interarm region for a particular galaxy. The black diamonds represent the mean values within each region; the error bars indicate the standard deviations. The distribution of values for each region are also shown in the right auxiliary panels.

more concentrated star formation in the arms for the grand design ones. We also find small differences in barred galaxies, not observed in unbarred systems, hinting that bars may affect the chemical distribution of these galaxies but not strongly enough as to be reflected in the overall abundance distribution. This entire analysis of arm and interarm abundance gradients performed with CALIFA data is described in [36].

4 Azimuthal abundance variations

Recently, with the advent of instruments that provide data covering large FoVs with high spatial resolution, systematic azimuthal variations of the gas oxygen abundance distribution have started to be measured, always focused on the study of individual galaxies [13, 44].

From a theoretical point of view, the presence of azimuthal variations induced by radial migration was recently proposed in simulations of spiral galaxies [8, 11]. Although these predictions were focused on the stellar component, it is known that both gas and stars are affected by these movements (e.g. [23, 10]). Indeed, streaming motions of gas along the spiral arms have been proposed [10, 1], which could produce azimuthal variations of the gas abundance.

In this thesis we take advantage again of the high spatial resolution of AMUSING data to analyse the presence of possible azimuthal abundance variations in one galaxy of the sample, NGC 6754, in order to better investigate the subtle differences found in the arm/interarm analysis performed with CALIFA data. This way, in order to measure azimuthal variations

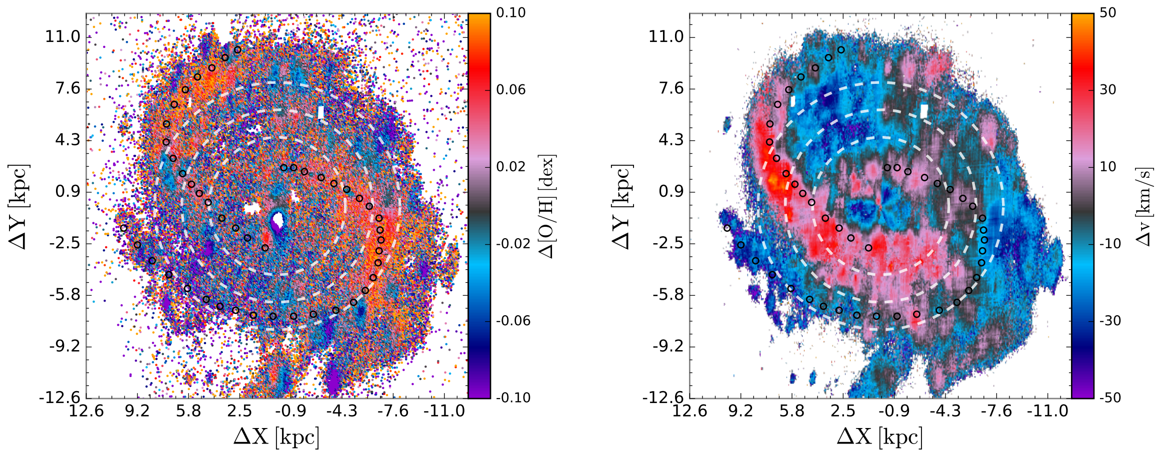

Figure 5: 2D deprojected distributions of the gas abundance (*left*), and Hα LOS velocity (*right*) residuals. Dashed white circles indicate the three radial positions R = 4.5, 6.3 and 8.1 kpc of the azimuthal profiles shown in Fig. 6.

in the abundance distribution of NGC 6754 we need to derive the abundance residuals (see left panel of Fig. 5) by removing the characteristic radial profile displayed by this galaxy to the observed 2D distribution. In addition to the abundance distribution, we also analyse for this galaxy the line-of-sight (LOS) Hα velocity distribution to find some possible links between kinematics and the observed pattern in the azimuthal abundance variations (as suggested by theoretical works). Similarly, the residual velocities (see right panel of Fig. 5) are obtained after subtracting the LOS projection of the derived rotation model to the observed distribution.

Analysing the azimuthal profiles of both residuals at three different galactocentric distances represented as dashed white circles in Fig. 5 (see Fig. 6), we find that the velocity profiles show a peak located just after the peak in the light distribution (leading side of the arm[1]), with an amplitude between $\sim 28-38$ km/s, and a minimum just before the light peak (trailing side). Remarkably, these maxima (minima) in the velocity profile appear together with a decrement (increment) in the abundance profile at all the radii, with a total amplitude (peak-to-peak) up to ~ 0.1 dex.

Considering the galaxy orientation and assuming trailing spiral arms [14], positive (negative) residual velocities indicate radially inward (outward) motions of the gas and tangentially faster (slower) motions of the gas for the eastern spiral arm. Thus, the positive velocity residuals displayed by NGC 6754 in a wide extension of the leading part of the eastern arm can be interpreted either as gas moving radially inward, gas moving tangentially faster, or a combination of both. Following a similar reasoning, the negative velocity residuals in the trailing part can be the result of gas moving radially outward, gas moving tangentially

[1]The leading side of a spiral arm is the edge of the arm that points towards the direction of disc rotation, that is, the front of the arm. The trailing side is, on the other hand, the edge of the arm that points towards the opposite direction of disc rotation, that is, the back of the arm.

slower, or both. The asymmetries found in the metallicity residuals are in agreement with a transport of metal-rich gas from the inner disc toward the outer regions at the trailing side of the spiral arm and more metal-poor gas from the outer disc toward the inner ones at the leading side, which is strikingly consistent with the velocity asymmetries mentioned above. These trends are observed at all three radii, which indicates strong evidence of the radial migration happening in a large radial range.

In other to interpret these results we also analyse the gas content of a simulated galaxy (N-body+SPH), which allows us to analyse separately the radial and tangential components of the LOS velocity. In light of the comparison between the observations and the simulations we conclude that the trailing (leading) edge of the NGC 6754 spiral arms show signatures of tangentially slower, radially outward (tangentially faster, radially inward) streaming motions of metal-rich (poor) gas over a large range of radii. These results show direct evidence of gas radial migration for the first time. In addition, the simulated galaxy displays spiral morphological features rotating with a similar speed as the gas at every radius. Although it is not guaranteed that the nature of the spiral arms in the observed galaxy is the same as in the simulations, the consistency found indicates that the spiral arm features in NGC 6754 may be transient, with a pattern speed decreasing with radius. A more detailed explanation of this analysis of NGC 6754 with AMUSING data can be found in [34].

5 Conclusions

The existence of a radial decrease in the gas chemical abundances of spiral galaxies was well established by observations decades ago (e.g. [38, 25, 17, 15, 27, 6]), supporting the inside-out scenario for disc evolution [20, 5]. With the advent of IFS surveys like CALIFA, abundance studies using larger samples of H II regions have become feasible [31, 29], with the same results as in previous studies.

In this thesis we go a step further and analyse for the first time the oxygen abundance distribution for a large sample of galaxies taking advantage of the full 2D information provided by the CALIFA and AMUSING surveys, improving the statistics over previous studies in the field. This way, it comprises the most complete 2D characterisation of the oxygen abundance distribution of the ionised gas in a large and statistically significant sample of spiral galaxies up to date. We show that, besides the negative gradient, this distribution displays a wide range of features such as inner drops, outer flattenings, and azimuthal variations, as opposed to the simplistic view of a single radial decline. These features display clear trends with galaxy properties such as spiral structure, mass, or bar presence. All these results provide strong constraints to chemical evolution models aimed at explaining the formation and evolution of spiral galaxies, contributing to improve our understanding of the Universe around us.

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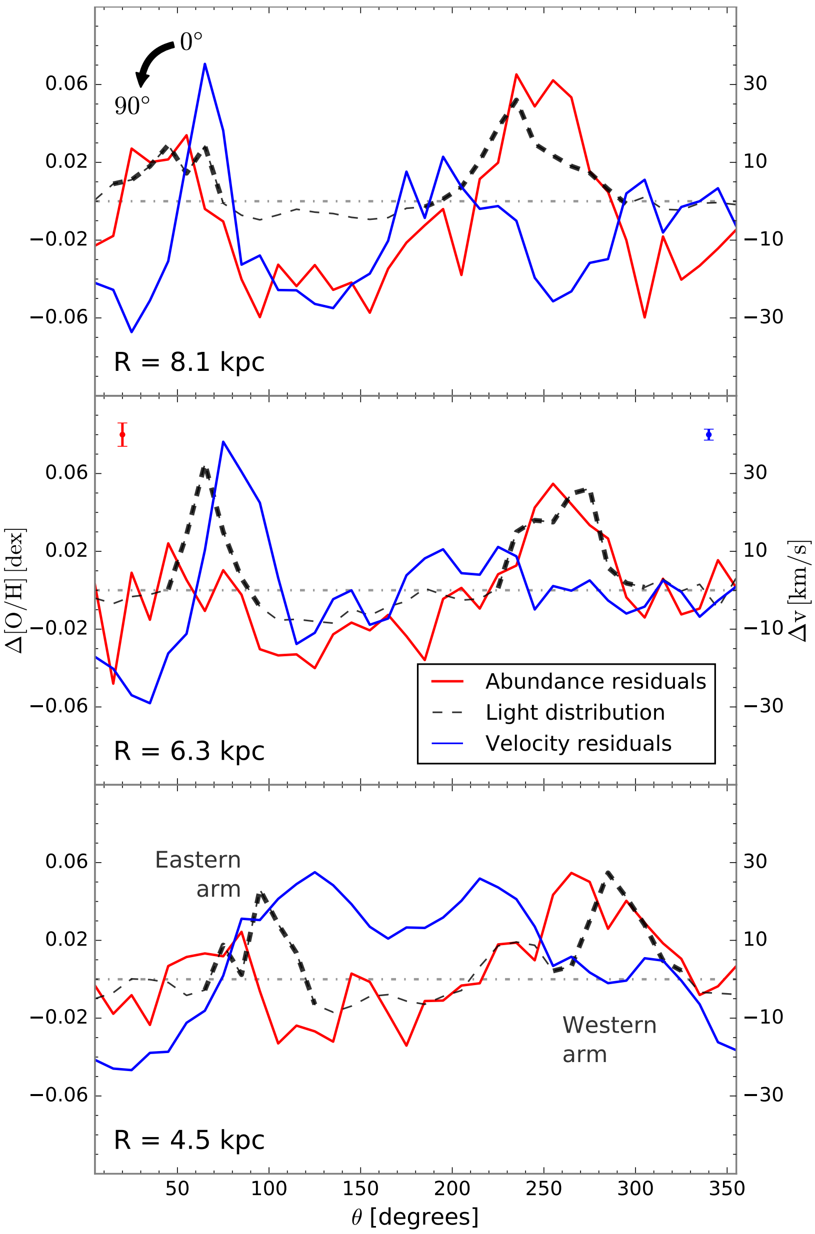

Figure 6: Azimuthal profiles of the light (black dashed), oxygen abundance residuals (blue, left-hand y-axis) and Hα LOS velocity residuals (red, right-hand y-axis) at three different radii (shown in Fig. 5). The position of the spiral arms is marked with the bold dashed line. Mean errors in the azimuthal profiles are denoted by the vertical lines in the middle panel. The angles are measured counter-clockwise from the positive Y-axis in Fig. 5.

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