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Integral field spectroscopy and multi-wavelength imaging of the nearby spiral galaxy NGC 5668: a case for MEGARA

R.A. Marino[1], A. Gil de Paz[1], A. Castillo-Morales[1], J.C. Muñoz-Mateos[2], S.F. Sánchez[3], P.G. Pérez-González[1], J. Gallego[1], J. Zamorano[1], A. Alonso-Herrero[4], and S. Boissier[5]

[1] CEI Campus Moncloa, UCM-UPM, Departamento de Astrofísica y CC. de la Atmósfera, Facultad de CC. Físicas, Universidad Complutense de Madrid, Avda. Complutense s/n, 28040 Madrid, Spain, `ramarino@fis.ucm.es`

[2] National Radio Astronomy Observatory

[3] Centro Astronómico Híspano Alemán, Calar Alto

[4] Instituto de Física de Cantabria

[5] Laboratoire dÁstrophysique de Marseille

Abstract

In order to improve our understanding of the mechanisms that drive the evolution of disk galaxies we analyze the full bi-dimensional spectral cube of the nearby spiral galaxy NGC 5668, which was obtained as a mosaic of 6 pointings, covering a total area of $2 \times 3\,\mathrm{arcmin}^2$, obtained with the PPAK Integral Field Unit at the Calar Alto (CAHA) observatory 3.5 m telescope. From these data we obtain the bidimensional spatial distribution maps of the attenuation of the ionized gas, and chemical abundances of oxygen. We find a mean ionized-gas attenuation of $A_V \sim 1$ mag, with the gas attenuation appearing larger than the continuum attenuation by a factor of 3. With respect to the oxygen abundance, we find that, while inwards of r ∼36"∼ 4.4kpc ∼ 0.36 ($\frac{D_{25}}{2}$) the derived O/H ratio follows the radial gradient typical of the disks of spiral galaxies, the abundance gradient beyond r∼ 36″ flattens out. The multi-wavelength surface brightness profiles of NGC 5668 are compared with those predicted by chemo-spectrophotometric evolutionary models of galaxy disks in the context of the inside-out scenario of disk formation. Both the deviations of the color profiles and the shape of the metallicity radial distribution indicate that a secondary mechanism, possibly gas transfer induced by the presence of a young bar, must have played a role in shaping the recent chemical and star formation histories of NGC5668 beyond what is predicted by the inside-out scenario. This study demonstrates the strength of the combination of IFU and multi-wavelength imaging data. With MEGARA, the future optical IFU & MOS for 10.4-m GTC we will fill the gap currently existing in astronomical instrumentation with high spectral resolution and large area coverage simultaneously addressing such fundamental issues in galactic structure and evolution.

1 Introduction

The formation and evolution of galactic disks remain two of the most important aspects in extragalactic astronomy. Despite significant progress in the recent past regarding our understanding of the history of both the thick and thin disks, important questions remain unanswered: How old are the disks seen in the spiral galaxies today? How did they chemically evolve? Are they growing inside-out, as proposed to explain the color and metallicity gradients in our own Milky Way? Do they have an edge? How efficient is the stellar radial diffusion? Until recently the study of the properties of spiral disks has been limited to broad-band imaging data and/or long-slit spectroscopy, which has severely limited the reach of previous works, [9] and [10]. Our effort is committed to add another dimension to the study of nearby spiral galaxies thanks to the use of wide-field integral-field spectrometers. In this work we present the study of the full bi-dimensional spectral cube of the nearby spiral galaxy NGC 5668, Fig. 1, which was obtained as a mosaic of 6 pointings by using the PPAK Integral Field Unit at the Calar Alto (CAHA) observatory 3.5 m telescope. These unprecedented sets of data have allowed us to get insights the properties of dust and star formation in galaxies.

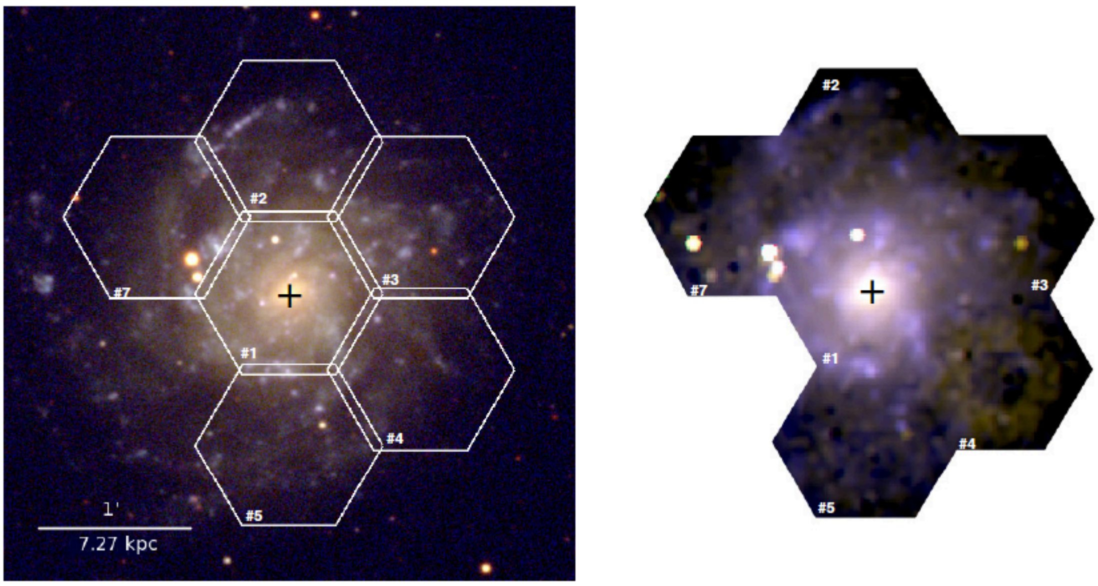

Figure 1: *Left panel:* False-color SDSS Optical image of NGC 5668. Plate scale is 0.396 arcsec/pix. *Right panel:* Synthetic false-color image obtained from the PPAK data cube and the response curves of the SDSS u, g and r filters. Plate scale is 1 arcsec/pix in this case. North is up and East is to the left in both cases.

2 The case of NGC 5668

NGC 5668 is a nearly face-on late-type spiral galaxy, that is classified Sc(s)II-III on the Hubble sequence. There is a weak bar or oval inner structure 12″ in size visible on the image, reflected by a small shoulder in the surface brightness profile published by [12]. The outer disk (beyond $R < 100''$) is slightly asymmetric and more extended towards the North. For this work we adopted a distance of 25 Mpc, $(m-M) = 31.99$ mag, assuming a cosmology with $H_0 = 73\,\mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega_{\mathrm{matter}} = 0.27$, $\Omega_{\mathrm{vacuum}} = 0.73$. NGC 5668 has been also recently observed by a number of facilities, including SAURON at the WHT, SDSS, Spitzer and the Medium-deep Imaging Survey of GALEX. This galaxy is also classified as a "supernova factory" due to the discovery of multiple supernova explotions in recent epoch [7]. This dataset in combination with the PPAK mosaic focus of this work should allow the most extensive analysis to date of their ionized-gas and stellar population properties.

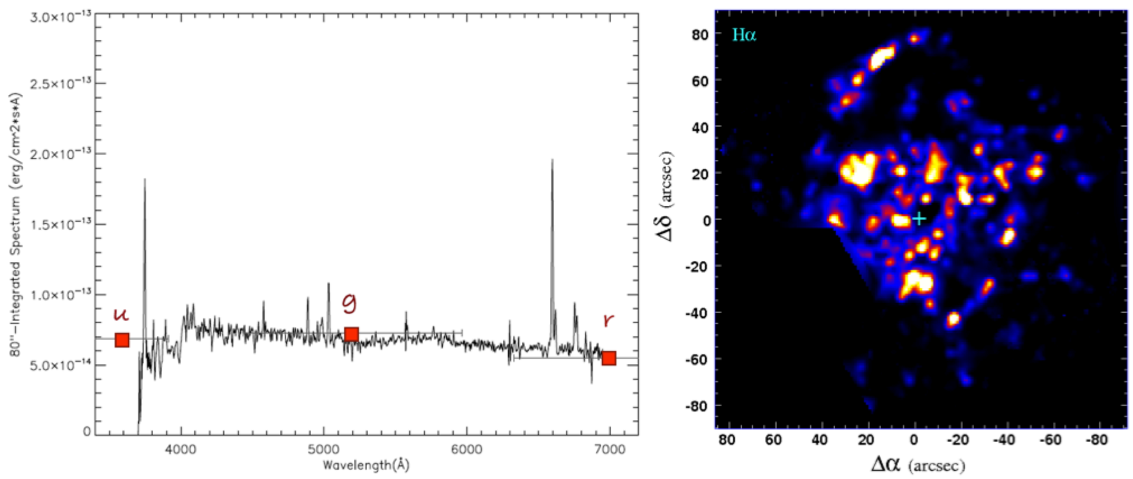

Figure 2: *Left panel:* The integrated spectrum of NGC 5668 is shown as a black line. The SDSS *g'* and *r'* band photometry data are shown as red squares. Horizontal error bars represent the FWHM of each filter. *Right panel:* Hα emission lines map. The mosaic center is marked with a cyan cross. North is up and East is to the left.

3 Observation and Data Reduction

We have observed the nearly face-on spiral galaxy NGC 5668 with the PPAK (Pmas fiber PAcK) IFU of PMAS, the Potsdam Multi-Aperture Spectrophotometer, at the Calar Alto (CAHA, Spain) observatory 3.5 m telescope. The observations were carried out on June 22-23-24, 2007. We used the PPAK mode that yields a total field-of view (FoV) of $74'' \times 65''$ (hexagonal packed) for each pointing, covering a total area of roughly $2 \times 3\,\mathrm{arcmin}^2$ (we obtained a mosaic of 6 PPAK pointings in order to study this relatively extended object). The final mosaic includes a total of 2292 raw-spectra, with 1982 science spectra that cover the broad spectral range 3700-7131 Å. The reduction procedure applied for NGC 5668 follows the techniques and sequence described in [11]. The reduction was carried out using R3D, a software package for reducing fiber-based spectroscopic data focused on the reduction of integral field spectroscopy of IFUs.

4 Analysis

We analyzed the synthetic map of the Hα emission line and selected 62 HII regions within the galaxy. We also generated continuum-corrected maps of the strongest collisionally excited- and permitted- emission lines: [OII]λ 3727; [OIII] $\lambda\lambda$ 4959, 5007; Hβ; [NII]λ6548; Hα (see Fig. 2); [NII]$\lambda6583, \lambda6548$ and [SII]$\lambda6717, \lambda6731$. In order to investigate the radial variation of the physical properties in the galaxy we also selected 18 concentric annuli, starting from the the center of the image (defined as the peak of the optical continuum emission), and continuing with the other annuli at increments of 5" in radius until reaching the outermost ring at $R_{\rm FINAL} = 95''$. The spectra were then corrected for reddening using the Balmer decrements from Hα and Hβ after adopting an intrinsic ratio of 2.86, [8]. Additionaly we verified that in the case of regions of high equivalent width in emission (typically no less than 5 $\AA$ in Hβ) the corrected Hβ/Hγ ratios were consistent with the predictions for case-B recombination value at a typical T_e. We also generate maps of ionized-gas extinction, radial velocity and stellar absorption equivalent width. An example is showed in Fig. 2 where we present the maps of the Hα line flux. Some advantages of using IFUs are that all the spectra are obtained simultaneously and that we can use the IFU as a large-aperture spectrograph. From our datacube we add up the spectra of all the fibers to create an integrated spectrum of NGC 5668 (Fig. 2) and we compare it with the corresponding fluxes derived from the SDSS finding a 8% difference between the two datasets.

5 Results

Many important topics in astrophysics involve the physics of ionized gases and the interpretation of their emission line spectra. For this reason we perform a full study of the spectroscopic properties of NGC 5668 and we obtain results for the electron density (from the [SII]6717 Å/ [SII]6731 Å ratio we compute a mean value for N_e of 190 cm^{-3}), for the dust attenuation (a significantly larger ionized-gas attenuation than that of the continuum is found), for the rotation curve and for the abundance gradient (here we will discuss only this latter, for more details see [5]).

The study of nebular abundances is crucial for understanding the chemical evolution of galaxies. In order to quantify the abundance gradient of NGC 5668 we follow the recipe by [4] (based on a combination of strong line methods such as the R_{23}). The oxygen abundance varies, according to the adopted recipe, between 12 + log(O/H) = 8.15 and 12 + log(O/H) = 8.7. We carried out three linear regressions to the data point, see Fig. 3, the first one is a fit for all points weighted by own errors that yields a gradient value of -0.035 dex kpc^{-1}, (-0.0042 dex arcsec^{-1}). The second and the third fits that we do are double fits on the data with a

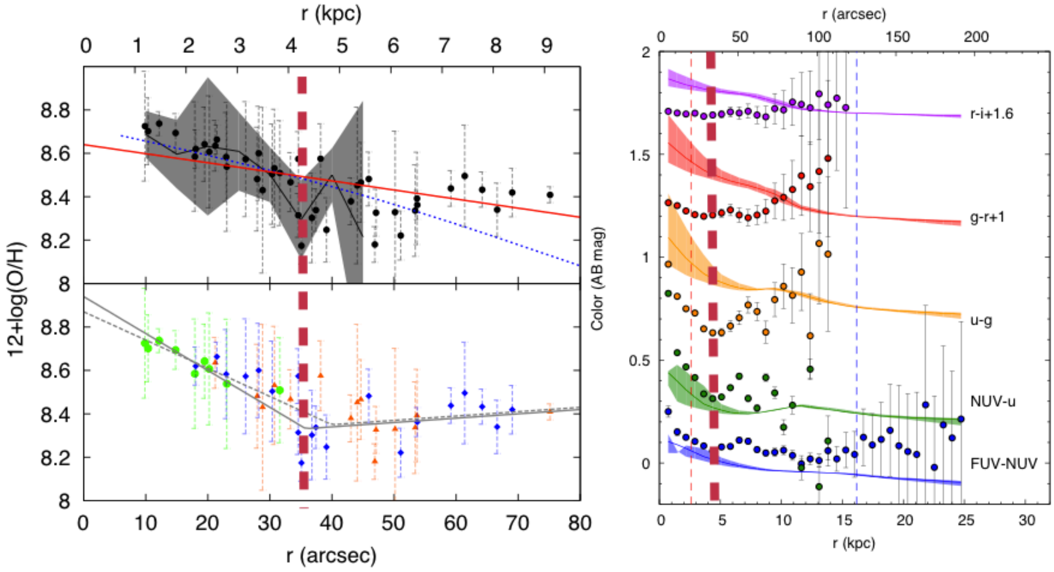

Figure 3: *Left panel:* Radial abundance gradient in NGC 5668, where filled-symbols correspond to individual H II regions while the grey-shaded area represents the values obtained for the concentric annuli. Top panel: The red line symbolizes the linear regression fit to the H II regions data. The blue dashed line represents the gradient obtained from the models of Boissier & Prantzos (1999, 2000). Bottom panel: In this plot we draw in grey (solid line) the double fit weighted by the errors. The grey dashed line reproduces the unweighted double fit. The color coding of the points represents the different line ratios used to calculate the metallicity for the central point of the ratios probability distribution: green points are calculated from [N II]/[0 II], red triangles from [N II]/Hα and blue diamonds show R_{23}-based values. *Right panel:* Observed color profiles of NGC 5668 (points) corrected for internal extinction. These observed colors are compared with the ones predicted by the best-fitting model to light profiles (lines and bands). The red and blue vertical dashed lines bracket the spatial range used during the fit.

free parameter, the radius of break, but one is weighted on the error points (black solid line) and the other one (dotted line) is unweighted. The main results that we find is that, while inwards of the optical edge the O/H ratio follows the radial gradient known from previous investigations, $12 + \log(\mathrm{O/H})_{r=0} = 8.9$ and a gradient value of -0.140 $\pm$ 0.016 (dex kpc^{-1}), the outer abundance trend, from a radius of 35.8$''$ ($\sim$4.4 kpc) flattens out to an approximately constant value of $12 + \log(\mathrm{O/H})_{r=0} = 8.27$ with a gradient of 0.002 $\pm$ 0.019 (dex kpc^{-1}) and even reverses, which might be interpreted in the context of the effects of stellar migration or it could implies different star formation histories between the inner and outer parts of the disk of this galaxy [2]. An abrupt discontinuity in the radial oxygen abundance trend is also detected near the optical edge of the disk. From the theoretical side a negative abundance gradient can be reproduced by *inside-out* scenarios of galaxy formation in which the timescale for the formation of the disk increases with galactocentric distance [6, 1, 3]. Surface brightness and color profiles from the UV to the near-infrared have been also obtained, see Fig. 3. These profiles nicely match the predictions of the chemo-spectrophotometrical models for the evolution of galaxy disks [1] for a circular velocity of $v_{\rm circ} = 167\,{\rm km\ s^{-1}}$ and a spin parameter of λ=0.053. This best-fitting model also agrees with the overall shape of the galaxy metallicity gradient and rotation curve although it cannot reproduce the steep-shallow metallicity break neither the moderate bluing in some of the color profiles ($u-g$, $g-r$) around the position of the metallicity break. While the overall observational properties of NGC 5668 are well fitted by the inside-out scenario of disk formation, the deviations in the color and metallicity profiles are best interpreted in the context of the presence of a nascent bar where significant in-situ star formation is (or have been recently) taking place. The formation of the bar is believed to be due to instabilities in the gas-rich inner disk of NGC 5668. This scenario is compatible with the relatively large HI content and star formation rate of NGC 5668 and with the presence of HVCs and HRVCs in its velocity field, evidence of significant non rotational gas motions in the disk.

6 Conclusions

We have investigated the properties of 62 individual HII regions within NGC 5668, that have been used to measure the abundance gradient at galactic scales. This has been combined with the analysis of the spectra of 18 concentric annuli and finally we analyze spectra that cover almost the entire spectral range from 3700 to 6700 Å. We use those data to estimate the attenuation, the electron density and the chemical abundance traced by the oxygen all with bi-dimensional spatial information. In addition we combine the IFU data with panchromatic broad-band images to obtain radial profiles and colors. Out of the different mechanisms proposed in the literature to explain the change in the slope of the metallicity profile in spiral disks (and the color profiles), only the presence of a bar in its formative stages agrees well with the other observational properties of NGC 5668. This study demonstrates the strength of the use of IFU data (especially when combined with multi-wavelength imaging) for deriving the bidimensional properties of disks in external galaxies. MEGARA, the future intermediate-resolution optical spectrograph of GTC, thanks to the depth and number of the studies being proposed, will allow studying the properties of stellar populations with an unprecedented combination of sensitivity and spectral resolution (R ∼6,000–20,000). These studies will allow deriving the star formation history of disks and, in particular, we should be able to test the *inside-out* scenario for the formation of disks and deviations from it, such as those associated to stellar migration, galaxy mergers, etc.

References

[1] Boissier, S. & Prantzos, N. 1999, MNRAS, 307, 857

[2] Bresolin, F., et al. 2009, ApJ, 700, 309

[3] Chiappini, C. et al. 2003, A&A, 410, 257

[4] Kewley, L. & Dopita, M. 2002, ApJ, 142, 35

[5] Marino, R. A. et al. 2012, ApJ, 754, 61

[6] Matteucci, F. & Francois, P. 1989, MNRAS, 239, 885

[7] Nakano, S., et al. 2004, IAUC, 8272, 1N

[8] Osterbrock, D. E. 1989, University Science Books

[9] Pohlen, M. & Trujillo, I. 2006, A&A, 454, 759

[10] Roskar, R. et al. 2008, ApJ, 65, 68

[11] Sánchez, S. F., et al. 2006, MNRAS

[12] Schulman, E., et al. 1996 AAS, 189, 608