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Integral Field Spectroscopy of the nearby spiral galaxy NGC 5668

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Abstract. 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 2×3 arcmin^2, obtained with the PPAK Integral Field Unit at the Calar Alto (CAHA) observatory 3.5 m telescope. From these data we derive maps of the attenuation of the ionized gas (from the $H\alpha$ / $H\beta$ Balmer decrement), electron density (from the [SII]6717Å/ [SII]6731Å ratio), and chemical abundances, of both oxygen (using either the T_e based method when possible or strong line methods such as the R_{23}), and nitrogen. In addition to these maps, we also extract the spectra of individual HII regions by adding the flux over several PPAK fibers to increase the signal-to-noise ratio of the spectra and reduce the uncertainties in the properties derived. Along with the study of the ionized gas we also embark in the analysis of the absorption-line spectrum dominating the bulge and inter-arm regions. The spectra of these regions are compared with the predictions of evolutionary synthesis models for evolved stellar populations. Both the measurements of spectroscopic indices and the full spectra will be used. Finally, given that most of the properties of the stars, gas, and dust in galaxies vary with radius; the spectra of concentric annuli are also extracted and analyzed.

Key words. Galaxy individual: NGC 5668, galaxy abundances, galaxy kinematics and dynamics, galaxy star cluster – Tecnique: spectroscopy

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, Pohlen & Trujillo (2006)

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and Roskar et al. (2008). 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. We have recently started a project to map a sample of a dozen nearby galaxies using mosaics obtained with the two largest IFU available to date: PPAK at the CAHA 3.5-m and VIMOS at ESO-VLT. In particular, these unprecedented sets of data have allowed us to get insights the properties of dust and star formation in galaxies. In this work we present the pilot 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. Despite the relatively modest collecting area of the CAHA 3.5-m telescope, the broad spectral coverage (from 3700 to 7000Å) and relatively good spectral resolution (R = 500) of PPAK make of this instrument the best tool for study stellar populations, dust content, and physical conditions of the gas (temperature, density, chemical abundances) in spatially resolved galaxies.

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 Schulman et al. (1996). 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, (Nakano et al. 2004). 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.

Fig. 1. SDSS Optical image (from 4458 to 7706Å) of NGC 5668. North is down and east is to the right. Plate scale is 0.396 arcsec/pix.

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 Sánchez et al. (2006). The reduction was carried out using R3D, a software package for reducing fiber-based spectroscopic data focused on the reduction of IFS of IFUs.

4. Analysis

The data were analyzed using tasks including in different packages in IRAF[1]. For a

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

few spectra we utlized IDL, Interactive Data Language. We analyzed the map of the $H\alpha$ emission line, the brightest line in the optical spectrum of HII regions under most physical conditions and selected 73 HII regions in the galaxy. We subtracted the continuum emission by using an image average of the two continuum maps adjacent to the emission lines. Finally, we also generated continuum-corrected maps of the strongest collisionally excited- and permitted- emission lines: [OII]λ3727; [OIII]$\lambda\lambda$4959, 5007; $H\beta$; [NII]λ6548; $H\alpha$; [NII]λ6583, λ6548 and [SII]λ6717, λ6731. In many spiral galaxies of early and intermediate Hubble type (Sa-Sc), active star formation is organized in a ring-like structure that often contains a large fraction of the entire star formation activity of the galaxy. To investigate this and 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 arcsec in radius until reaching the outermost ring at $R_{FINAL} = 95''$. The spectra were then corrected for reddening using the Balmer decrements from $H\alpha$ y $H\beta$ after adopting an intrinsic ratio of 2.86, Osterbrock (1989). Additionaly we verified that in the case or regions of high equivalent width in emission (typically no less than 5 Å in $H\beta$) the corrected $H\beta/H\gamma$ ratios were consistent with the predictions for case-B recombination value at a typical T_e.

5. Results

ATTENUATION: We utilized tree different methods to estimate the attenuation of the stellar continuum from the UV data available on NGC 5668. In Figure 2 we summarize these estimates. The gas attenuation appears larger than the continuum attenuation. This is somewhat expected given that, as shown in Calzetti et al. (1994), there is an almost factor of two difference among the two. The dust attenuation has a mean value of 1 magnitude, that is in agreement for what is found for spiral galaxies (e.g. Gil de Paz et al. 2007).

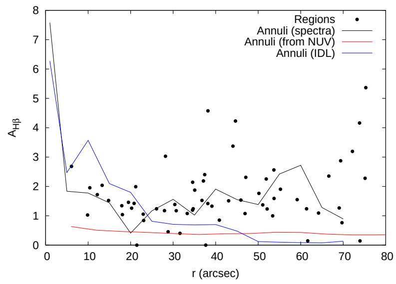

Fig. 2. Representation of radial variation of the dust attenuation. Filled circles represent the values obtained from individual HII regions based on the Balmer decrement. The black line represents Balmer decrement data for the concentric annuli. The red line is the attenuation trend calculated from the slope of the UV continuum (or, equivalently, the FUV-NUV color). The blue line show the attenuation that we find for the stellar continuum at optical wavelengths with our IDL fitting routine.

ELECTRON DENSITY: The electron density, N_e, is one of the key physical parameters needed to characterise a gaseous nebula. In our case, we make use of the $[SII]\lambda6716, \lambda6731$ line ratio. In order to properly estimate this electron density a previous knowledge on the electron temperature of the region responsible for the emissin [SII] lines is required. We then first estimated the T[NII] from the NII/NII ratio adopting the relation by McCall et al. (1984) and assumed a difference of 3000 K between T[NII] and T[SII], with the former being lowerGarnett (1992). Note that although this estimate for the temperature is not very precise (as it does not rely on the use of temperature-sensitive line ratios) is accurate enough for correcting the densities obtained from the SII/SII line ratio for temperature effects. Despite the uncertainties associated to the determination of T[SII], we find a mean value for N_e of $190 cm^{-3}$ for the regions, in agreement with the mean value, Osterbrock (1989).

METALLICITY: We also estimate chemical abundances and we find that, while inwards of the optical edge the O/H ratio follows the radial gradient known from previous investigations, the outer abundance trend flattens out to an approximately constant value.

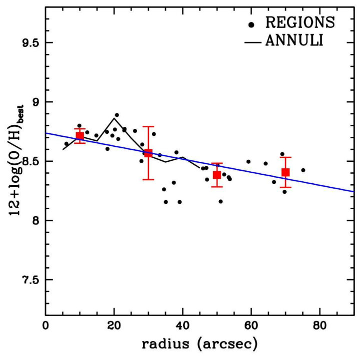

Fig. 3. Representation of the Oxygen abundance versus radius; filled-circles correspond to individual HII regions while the black line represents the values obtained for the concentric annuli. The red squares are the mean values binned in intervals of 20″ and the blue line represents the linear regression of those mean values, with a reduced $\chi^2 = 0.78$.

The latter varies, according to the adopted diagnostic, between $12 + log(O/H) = 8.15$ and $12 + log(O/H) = 8.7$ (i.e. from approximately 1/3 the solar oxygen abundance to nearly the solar value). An abrupt discontinuity in the radial oxygen abundance trend is also detected near the optical edge of the disk. We choose as the best set of values for the oxygen abundance those given by theKewley & Dopita (2002) recipe. The result of the application of these Kewley & Dopita recipe indicators to our HII region sample is shown in Figure 3, where we plot O/H abundances as a function of the galactocentric distance. The abundance gradient derived,$-0.058 dex/kpc$ ($-0.007 dex/arcsec$), is somewhat smaller than the one for the Milky Way ($0.08 dex/kpc$; Boissier et al. (1999) and references therein). One possible explication for the relatively shallow abundance gradient observed in the case of concentric annuli is that the continuum contribution for the annuli is much more strong than for the individual HII regions, so this reduce the emission equivalent width and make the continuum subtraction critical, which leads to more uncertain underlying absorption corrections in the $H\beta$ lines and, therefore, reddening corrections.

6. Conclusions

Many important topics in astrophysics involve the physics of ionized gases and the interpretation of their emission line spectra. The distribution of HII region is an excellent tracer of recent massive star formation in spiral galaxies and spectra can reveal details surrounding the first generations of star birth and the formation of the heavy elements in the young universe. We investigated the properties of 73 individual HII regions within NGC 5668, HII regions in nearby galaxies such as NGC 5668 may also be used to measure any possible metal abundance gradient at galactic scales and to investigate this, we also selected 18 concentric annuli, and finally we analize spectra that cover almost the entire spectral range from 3700 to 6700 Å. We use those data to estimate the attenuation (from the $H\alpha$ / $H\beta$ Balmer decrement), the electron density (from the [SII]6717 Å / [SII]6731 Å ratio), and the chemical abundance traced by the oxygen (using strong-line methods such as the R_{23}; Kewley & Dopita (2002)) and nitrogen (assuming that $N/O = N^+/O^+$ (e.g. Pagel et al. 1992)) of the ionized gas, all with bi-dimensional spatial information.

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