Star-forming Dwarf Galaxies: Ariadne’s Thread in the Cosmic Labyrinth

Star Formation in H\textsc{ii} Galaxies. Properties of the ionized gas

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Abstract.
We present two high signal-to-noise spectrophotometric observations of three and seven compact and luminous H\textsc{ii} galaxies observed with the WHT and the 3.5 m telescope at CAHA, respectively. All the observations have been made with the use of a double-arm spectrograph which provides spectra with a wide wavelength coverage, from 3200 to 10500 Å for the WHT data and 3400 to 10400 Å for the CAHA data, of exactly the same region of a given galaxy. These spectral ranges include the [O\textsc{ii}]\,\lambda\lambda\,3727,29 Å lines, the [S\textsc{iii}]\,\lambda\lambda\,9069,9532 Å doublet as well as various weak auroral lines such as [O\textsc{iii}]\,\lambda\,4363 Å and [S\textsc{iii}]\,\lambda\,6312 Å.

We propose a methodology to perform a self-consistent analysis of the physical properties of the emitting gas of H\textsc{ii} galaxies adequate to the data that can be obtained with the XXI century technology. This methodology requires the production and calibration of empirical relations between the different line temperatures that should supersede currently used ones based on very simple, and poorly tested, photo-ionization model sequences. Then, these observations are analysed applying a methodology designed to obtain accurate elemental abundances of oxygen, sulphur, nitrogen, neon, argon and iron in the ionized gas. Four electron temperatures and one electron density are derived from the observed forbidden line ratios using the five-level atom approximation. For our best objects errors of 1% in the [O\textsc{iii}] and 3% in the [O\textsc{ii}] and 5% in the [S\textsc{iii}] are achieved with a resulting accuracy between 5 and 9% in total oxygen abundances, O/H. These accuracies are expected to improve as better calibrations based on more precise measurements, both on electron temperatures and densities, are produced.

For the objects observed with the WHT we have compared the measurements obtained for our spectra with those performed on the spectra downloaded from the SDSS DR3 finding a satisfactory agreement.

The ionization structure of the nebulae can be mapped by the theoretical oxygen and sulphur ionic ratios, on the one side, and the corresponding observed emission line ratios, on the other – the $\eta$ and $\eta'$ plots –. The combination of both is shown to provide a means to test photo-ionization model sequences currently applied to derive elemental abundances in H\textsc{ii} galaxies. The ionization structure found for the observed objects from the O$^+$/O$^{3+}$ and S$^+$/S$^{2+}$ ratios points to high values of the ionizing radiation, as traced by the values of the “softness parameter” $\eta$ which is less than one for all the objects. The use of line temperatures derived from $t_e$([O\textsc{ii}]) based on current photo-ionization models yields for the two highest excitation objects much higher values of $\eta$ which would imply lower ionizing temperatures. This is however inconsistent with the ionization structure as probed by the measured emission line intensity ratios.

Finally, we have measured the T(Bac) for three of the H\textsc{ii} galaxies and computed temperature fluctuations. Only for one of the objects, the temperature fluctuation is significant and could lead to higher oxygen abundances by about 0.20 dex.
1. Introduction

H\textsc{ii} galaxies are low mass irregular galaxies with, at least, a recent episode of violent star formation\cite{8, 9} concentrated in a few parsecs close to their cores. The ionizing fluxes originated by these young massive stars dominate the light of this subclass of Blue Compact Dwarf galaxies (BCDs) which show emission line spectra very similar to those of giant extragalactic H\textsc{ii} regions (GEHRs; \cite{13, 2}). Therefore, by applying the same measurement techniques as for H\textsc{ii} regions, we can derive the temperatures, densities and chemical composition of the interstellar gas in this type of generally metal-deficient galaxies\cite{16, 7, 5}. In some cases, it is possible to detect in these objects, intermediate-to-old stellar populations which have a more uniform spatial distribution than the bright and young stellar populations associated with the ionizing clusters\cite{14}. This older population produces a characteristic spectrum with absorption features which mainly affect the hydrogen recombination emission lines\cite{1}, that is the Balmer and Paschen series in the spectral range of our interest. In some cases, the underlying stellar absorptions can severely affect the ratios of H\textsc{i} line pairs and hence the determination of the reddening constant [c(H\textbeta)]. They must therefore be measured with special care.

Spectrophotometry of bright H\textsc{ii} galaxies in the Local Universe allows the determination of abundances from methods that rely on the measurement of emission line intensities and atomic physics. This is referred to as the “direct” method. In the case of more distant or intrinsically fainter galaxies, the low signal-to-noise obtained with current telescopes precludes the application of this method and empirical ones based on the strongest emission lines are required. The fundamental basis of these empirical methods is reasonably well understood (see e.g. \cite{11}). The accuracy of the results however depends on the goodness of their calibration which in turn depends on a well sampled set of precisely derived abundances by the “direct” method so that interpolation procedures are reliable.

The precise derivation of elemental abundances however is not a straightforward matter. Firstly, accurate measurements of the emission lines are needed. Secondly, a certain knowledge of the ionization structure of the region is required in order to derive ionic abundances of the different elements and in some cases photo-ionization models are needed to correct for unseen ionization states.

An accurate diagnostic requires the measurement of faint auroral lines covering a wide spectral range and their accurate (better than 5\%) ratios to Balmer recombination lines. These faint lines are usually about 1\% of the H\textbeta intensity. The spectral range must include from the UV [O\textsc{ii}] \lambda\lambda 3727,29 Å doublet, to the near IR [S\textsc{iii}] \lambda 9069,9532 Å lines. This allows the derivation of the different line temperatures: T_e([O\textsc{ii}]), T_e([S\textsc{ii}]), T_e([O\textsc{iii}]), T_e([S\textsc{iii}]), T_e([N\textsc{ii}]), needed in order to study the temperature and ionization structure of each H\textsc{ii} galaxy considered as a multizone ionized region.

Unfortunately most of the available starburst and H\textsc{ii} galaxy spectra have only a restricted wavelength range (usually from about 3600 to 7000 Å), consequence of observations with single arm spectrographs, and do not have the adequate signal-to-noise ratio (S/N) to accurately measure the intensities of the weak diagnostic emission lines. Even the Sloan Digital Sky Survey (SDSS) spectra\cite{15} do not cover simultaneously the [O\textsc{ii}] \lambda 3727,29 and the [S\textsc{ii}] \lambda 9069 Å lines, they only represent an average inside a 3 arcsec fibre and reach the required signal-to-noise ratio only for the brightest objects. We have therefore undertaken a project with the aim of obtaining a database of top quality line ratios for a sample that includes the best objects for the task. The data is collected using exclusively two arm spectrographs in order to guarantee both high quality spectrophotometry in the whole spectral range from 3500 to 10500 Å approximately, and good spectral and spatial resolution. In this way we are able to vastly improve constraints on the photo-ionization models including the mapping of the ionization structure and the measurement of temperature fluctuations about which very little is known.

It is important to realize that the combination of accurate spectrophotometry and wide spectral coverage cannot be achieved using single arm spectrographs where, in order to reach the necessary spectral resolution, the wavelength range must be split into several independent observations. In those
cases, the quality of the spectrophotometry is at best doubtful mainly because the different spectral ranges are not observed simultaneously.

2. Observations and data reduction

2.1. WHT observations

The blue and red spectra were obtained simultaneously using the Intermediate dispersion Spectrograph and Imaging System (ISIS) double beam spectrograph mounted on the 4.2m William Herschel Telescope (WHT) of the Isaac Newton Group (ING) at the Roque de los Muchachos Observatory, on the Spanish island of La Palma. They were acquired on July the 18th 2004 during one single night observing run and under photometric conditions. EEV12 and Marconi2 detectors were attached to the blue and red arms of the spectrograph, respectively. The R300B grating was used in the blue covering the wavelength range 3200-5700 Å (centered at $\lambda_\text{c} = 4450$ Å), giving a spectral dispersion of $0.86 \, \text{Å pixel}^{-1}$. On the red arm, the R158R grating was mounted providing a spectral range from 5500 to 10550 Å ($\lambda_\text{c} = 8025$ Å) and a spectral dispersion of $1.64 \, \text{Å pixel}^{-1}$. The pixel size for this set-up configuration is 0.2 arcsec for both spectral ranges. The slit width was $\sim0.5$ arcsec, which, combined with the spectral dispersions, yielded spectral resolutions of about 2.5 and 4.8 Å FWHM in the blue and red arms respectively. All observations were made at paralactic angle to avoid effects of differential refraction in the UV.

The instrumental configuration was planned in order to cover the whole spectrum from 3200 to 10550 Å providing at the same time a moderate spectral resolution. This guarantees the simultaneous measurement of the Balmer discontinuity and the nebular lines of [OII] $\lambda\lambda 3727,29$ and [SIII] $\lambda\lambda 9069,9532$ Å at both ends of the spectrum, in the very same region of the galaxy. A good signal-to-noise ratio was also required to allow the detection and measurement of weak lines such as [OIII] $\lambda 4363$, [SII] $\lambda\lambda 4068, 6717$ and 6731, and [SIII] $\lambda 6312$.

2.2. CAHA observations

Blue and red spectra were obtained simultaneously using the double beam Cassegrain Twin Spectrograph (TWIN) mounted on the 3.5m telescope of the Calar Alto Observatory at the Complejo Astronómico Hispano Alemán (CAHA), Spain. They were acquired in June 2006, during a four night observing run and under excellent seeing and photometric conditions. Site#22b and Site#20b, 2000 × 800 px 15 µm, detectors were attached to the blue and red arms of the spectrograph, respectively. The T12 grating was used in the blue covering the wavelength range 3400-5700 Å (centered at $\lambda_\text{c} = 4550$ Å), giving a spectral dispersion of $1.09 \, \text{Å pixel}^{-1}$ ($R \approx 4170$). On the red arm, the T11 grating was mounted providing a spectral range from 5800 to 10400 Å ($\lambda_\text{c} = 8100$ Å) and a spectral dispersion of $2.42 \, \text{Å pixel}^{-1}$ ($R \approx 3350$). The pixel size for this set-up configuration is 0.56 arcsec for both spectral ranges. The slit width was $\sim1.2$ arcsec, which, combined with the spectral dispersions, yielded spectral resolutions of about 3.2 and 7.0 Å FWHM in the blue and the red respectively.

Again, all observations were made at paralactic angle to avoid effects of differential refraction in the UV. The instrumental configuration covers the whole spectrum from 3400 to 10400 Å (with a gap between 5700 and 5800 Å) providing at the same time a moderate spectral resolution.
2.3. Data reduction

All the images were processed and analysed with IRAF routines in the usual manner. The procedure includes the removal of cosmic rays, bias subtraction, division by a normalized flat field and wavelength calibration.

For a complete discussion about instrumental configuration, data reduction procedure, results, method of abundance determinations and ionization structure see [4, 3].

3. Summary and conclusions

We have performed a detailed analysis of newly obtained spectra of three and seven Hii galaxies observed with the 4.2 m WHT and the 3.5 CAHA telescopes, respectively. These galaxies were selected from the Sloan Digital Sky Survey Data Release 2 and 3, respectively. For the first set of galaxies the spectra cover from 3200 to 10550 Å in wavelength, while for the second group the data cover from 3400 to 10400 Å with a gap of approximately 100 Å between 5700 and 5800 Å. The WHT spectra have a FWHM resolution of about 1800 in the blue and 1700 in the red spectral regions, and the CAHA ones of about 1400 and 1200, respectively.

The high signal-to-noise ratio of the obtained spectra allows the measurement of four line electron temperatures: $T_e([\text{Oiii}])$, $T_e([\text{Siii}])$, $T_e([\text{Oii}])$ and $T_e([\text{Sii}])$, for all the objects of the sample with the addition of $T_e([\text{Nii}])$ for three of them, and the Balmer continuum temperature $T(Bac)$ for the WHT objects. These measurements and a careful and realistic treatment of the observational errors yield total oxygen abundances with accuracies between 5 and 12%. The fractional error is as low as 1% for the ionic $\text{O}^2+/\text{H}^+$ ratio due to the small errors associated with the measurement of the strong nebular lines of $[\text{Oii}]$ and the derived $T_e([\text{Oii}])$, but increases up to 30% for the $\text{O}^+/\text{H}^+$ ratio. The accuracies are lower in the case of the abundances of sulphur (of the order of 25% for $\text{S}^+$ and 15% for $\text{S}^{2+}$) due to the presence of larger observational errors both in the measured line fluxes and the derived electron temperatures. The error for the total abundance of sulphur is also larger than in the case of oxygen (between 15% and 30%) due to the uncertainties in the ionization correction factors.

This is in contrast with the unrealistically small errors quoted for line temperatures other than $T_e([\text{Oii}])$ in the literature, in part due to the commonly assumed methodology of deriving them from the measured $T_e([\text{Oii}])$ through a theoretical relation and calculating the errors simply by propagating statistically the $T_e([\text{Oii}])$ ones. These relations are found from photo-ionization model sequences and no uncertainty is attached to them although large scatter is found when observed values are plotted; usually the line temperatures obtained in this way carry only the observational error found for the $T_e([\text{Oii}])$ measurement and does not include the observed scatter, thus heavily underestimating the errors in the derived temperature.

In fact, no clear relation is found between $T_e([\text{Oii}])$ and $T_e([\text{Oii}])$ for the existing sample of objects. A comparison between measured and model derived $T_e([\text{Oii}])$ shows than, in general, model predictions overestimate this temperature and hence underestimate the $\text{O}^+/\text{H}^+$ ratio. This, though not very important for high excitation objects, could be of some concern for lower excitation ones for which total O/H abundances could be underestimated by up to 0.2 dex. It is worth noting that the objects observed with double-arm spectrographs, therefore implying simultaneous and spatially coincident observations over the whole spectral range, show less scatter in the $T_e([\text{Oii}]) - T_e([\text{Oii}])$ plane clustering around the $N_e = 100 \text{ cm}^{-3}$ photo-ionization model sequence. On the other hand, this small scatter could partially be due to the small range of temperatures shown by these objects due to possible

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selection effects. This small temperature range does not allow either to investigate the metallicity effects found in the relations between the various line temperatures in recent photo-ionization models by [6].

Also, the observed objects, though showing Ne/O and Ar/O relative abundances typical of those found for a large HII galaxy sample [12], show higher than typical N/O abundance ratios that would be even higher if the [OII] temperatures would be found from photo-ionization models. We therefore conclude that the approach of deriving the O+ temperature from the O2+ one should be discouraged if an accurate abundance derivation is sought.

These issues could be addressed by re-observing the objects listed in Table 13 of [3], which cover an ample range in temperatures and metal content, with double arm spectrographs. This sample should be further extended to obtain a self consistent sample of about 50 objects with high signal-to-noise ratio and excellent spectrophotometry covering simultaneously from 3600 to 9900 Å. This simple and easily feasible project would provide important scientific return in the form of critical tests of photo-ionization models.

For the WHT objects, we have compared our obtained spectra with those downloaded from the SDSS DR3 finding a satisfactory agreement. The analysis of these spectra yields values of line temperatures and elemental ionic and total abundances which are in general agreement with those derived from the WHT spectra, although for most quantities, they can only be taken as estimates since, due to the lack of direct measurements of the required lines, theoretical models had to be used whose uncertainties are impossible to quantify. Unfortunately, the spectral coverage of SDSS precludes the simultaneous observation of the [OIII]λ3727,29 Å and [SII]λ9069, 9532 Å lines, and therefore the analysis can never be complete.

The ionization structure found for the observed objects from the O+/O2+ and S+/S2+ ratios for all the observed galaxies, except one, cluster around a value of the “softness parameter” η of 1 implying high values of the stellar ionizing temperature. For the discrepant object, showing a much lower value of η, the intensity of the [OII]λ7319,25 Å lines are affected by atmospheric absorption lines. When the observational counterpart of the ionic ratios is used, this object shows a ionization structure similar to the rest of the observed ones. This simple exercise shows the potential of checking for consistency in both the η and η′ plots in order to test if a given assumed ionization structure is adequate. In fact, these consistency checks show that the stellar ionizing temperatures found for the observed HII galaxies using the ionization structure predicted by state of the art ionization models result too low when compared to those implied by the corresponding observed emission line ratios. Therefore, metallicity calibrations based on abundances derived according to this conventional method are probably bound to provide metallicities which are systematically too high and should be revised.

Finally, we have measured the Balmer continuum temperature for the three WHT objects and derived the temperature fluctuations as defined by [10]. Only for one of the objects, the temperature fluctuation is significant and could lead to higher oxygen abundances by about 0.20 dex.

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