ON THE COMPACT H II GALAXY UM 408 AS SEEN BY GMOS–IFU: PHYSICAL CONDITIONS

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ABSTRACT

We present Integral Field Unit GMOS–IFU data of the compact H II galaxy UM 408, obtained at the Gemini South telescope, in order to derive the spatial distribution of emission lines and line ratios, kinematics, plasma parameters, and oxygen abundances as well the integrated properties over an area of 3′′×4.′4 equivalent with ∼750 pc × 1100 pc located in the central part of the galaxy. The starburst in this area is resolved into two giant regions of about 1′′5 and 1′′ (~750 pc and ∼250 pc) diameter, respectively and separated 1.5–2′′ (~500 pc). The extinction distribution concentrate its highest values close but not coincident with the maxima of Hα emission around each one of the detected regions. This indicates that the dust has been displaced from the exciting clusters by the action of their stellar winds. The ages of these two regions, estimated using Hβ equivalent widths, suggest that they are coeval events of ∼5 Myr with stellar masses of ~104 M☉. We have also used [O III]/Hβ and [S II]/Hα ratio maps to explore the excitation mechanisms in this galaxy. Comparing the data points with theoretical diagnostic models, we found that all of them are consistent with excitation by photoionization by massive stars. The Hα emission line was used to measure the radial velocity and velocity dispersion. The heliocentric radial velocity shows an apparent systemic motion where the east part of the galaxy is blueshifted, while the west part is redshifted, with a relative motion of ~10 km s⁻¹. The velocity dispersion map shows supersonic values typical for extragalactic H II regions. We derived an integrated oxygen abundance of 12+log(O/H) = 7.87 summing over all spaxels in our field of view. An average value of 12+log(O/H) = 7.77 and a difference of Δ(O/H) = 0.47 between the minimum and maximum values (7.58 ± 0.06–8.05 ± 0.04) were found, considering all data points where the oxygen abundance was measured. The spatial distribution of oxygen abundance does not show any significant gradient across the galaxy. On the other hand, the bulk of data points are lying in a region of ±2σ dispersion (with σ = 0.1 dex) around the average value, confirming that this compact H II galaxy, like other previously studied dwarf irregular galaxies, is chemically homogeneous. Therefore, the new metals processed and injected by the current star formation episode are possibly not observed and reside in the hot gas phase, whereas the metals from previous events are well mixed and homogeneously distributed through the whole extent of the galaxy.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: individual (UM 408) – galaxies: ISM

Online-only material: color figures

1. INTRODUCTION

H II galaxies (or blue compact dwarfs, BCDs) are low-mass and metal-poor galaxies (1/50–1/3 Z☉), experiencing strong episodes of star formation, characterized by the presence of bright emission lines on a faint blue continuum (Terlevich et al. 1991; Kehrig et al. 2004). Several studies (e.g., Papaderos et al. 1996; Telles & Terlevich 1997; Cairós et al. 2003; Westera et al. 2004) have shown the existence of an old stellar population underlying the present burst in most of these galaxies, indicating that these objects are not young systems forming their first generation of stars.

The star formation activity in H II galaxies is concentrated in several luminous star clusters (∼1–30 pc in size) spread over the galaxies. Some of these clusters have been associated with super star clusters (SSCs), similar to those found in interacting galaxies, such as the antennae (Whitmore & Schweizer 1995; Whitmore et al. 1999), and some local dwarf galaxies such as Henize 2–10 (Conti & Vacca 1994) and NGC 1569 (e.g., O’Connell et al. 1994; Arp & Sandage 1985). During their evolution, these clusters ionize the interstellar medium (ISM) causing the formation of giant H II regions (GHIIRs), and release a considerable quantity of mechanical energy into the ISM, characterized by supersonic motions (e.g., Melnick et al. 1987), sweeping up the surrounding medium, removing the gas and dust from the star formation site, while producing structures such as bubbles and supershells. Ultimately, the evolution of these young clusters also causes the freshly produced metals to be dumped into the ISM.

Oxygen and other α elements are produced by massive stars (>8–10 M☉) and are released into the ISM during their supernova (SN) phase. These metals will be dispersed in the whole galaxy and mixed via hydrodynamic mechanisms in timescales of few 10⁸ yr (e.g., Tenorio-Tagle 1996). Since the spatial distribution of abundances of O, N, etc., depends on the recycling time of the ISM, the spatial variation of these abundances give important insights about these processes. The spatial distribution of emission line ratios and of the abundance of certain elements in dwarf galaxies have been studied by different authors (e.g., Kobulnicky & Skillman 1996, 1997; Lee...
and Kobulnicky et al. 1997), but no oxygen localized enrichment systems have been confirmed (Kobulnicky & Skillman 1996). In GHIIRs, where only one star formation region is present, it is usually assumed that the abundance of the galaxy and their ISM is well represented by the abundance of this single region, assuming that the metals are well mixed and distributed across the galaxy.

The details of the structure of H II galaxies are important to understand their ionization mechanisms, star formation feedback, and chemical enrichment. These issues have been actively addressed in studies of the brightest and nearest systems. The large and heterogeneous H II galaxy sample (Loose & Thuan 1986; Kunth et al. 1988; Telles et al. 1997) includes a significant number of far less studied objects at larger distances, with small apparent sizes and with relatively low surface brightness. Typically, H II galaxies contain one or a few star formation regions, but H\(\beta\) images (Lagos et al. 2007) of some compact objects have revealed that the central region probably hosts a myriad of unresolved star clusters. The present facilities, with high spatial resolution and high-efficiency instruments on large telescopes (8 m), allow us to study these more distant objects to derive their observed properties and relate them to the better known nearby galaxies, thus having a handle on the intrinsic properties of star formation as well as possible evolutionary effects.

In this paper, we use integral field spectroscopy with the Gemini Multiobject Spectrograph and the Integral Field Unit (GMOS–IFU) at Gemini South in order to study the spatial distribution of emission lines, their ratios, extinction, abundances, and the kinematic properties of the gas in the ISM of the compact dwarf galaxy UM 408. UM 408 belongs to a subset sample of rare H II galaxies with low metal abundances (i.e., \(Z < 1/20 Z_{\odot}\)) with \(12 + \log(O/H) = 7.66\) (Masegosa et al. 1994; Telles 1995), compact morphology, and very small effective radius \((R_{\text{eff}})\) of only \(2\,\prime\)1 from previous morphology and surface brightness studies (Telles & Terlevich 1997). On the other hand, Pustilnik et al. (2002) using high-resolution spectroscopy derived an abundance of \(12 + \log(O/H) = 7.93\) and H I observations (Salzer et al. 2002) reveal an H I mass of \(\log(M_{\text{HI}}) = 8.815\, M_{\odot}\). UM 408 is cataloged by Salzer (1989) as a dwarf H II hot spot with a redshift of \(0.0127\) \((v = 3598\, \text{km s}^{-1})\) with coordinates R.A. = 02\(^{h}\)11\(^{m}\)23\(^{s}\), Decl. = 02\(^{\circ}\)20\(^{\prime}\)30\(^{\prime\prime}\) (J2000) at a distance of \(\sim 46\, \text{Mpc}\), and V apparent magnitude of 17.38. With the present observations, we note that the central part of UM 408 encompasses two main star formation regions (here named A and B), as shown by the g-band acquisition images in Figure 1. Another faint region, called C, can be seen in the outer parts of the galaxy. These regions were all unresolved in previous studies.

The observations and data reduction procedures are discussed in Section 2. Section 3 gives the results obtained from the two-dimensional emission line maps. In Section 4, we discuss our results and our conclusions are presented in Section 5.

2. OBSERVATIONS AND DATA REDUCTIONS

The observations were performed with the GMOS (Hook et al. 2004) and the IFU unit (Allington-Smith et al. 2002) at the Gemini South Telescope in Chile during the night of 2004 August 21 and December 31, using the grating B600+_G5323 (B600) and on 2005 January 1 with the grating R600+_G5324 (R600) in one slit mode, covering a total spectral range from \(\sim 3021\) to 7225 \(\AA\). The GMOS–IFU in one slit mode composes a pattern of 750 hexagonal elements, each with a projected diameter of 0.2, covering a total 3\(^{\prime}\)5 \(\times\)5\(^{\prime}\) field of view, where 250 of these elements are dedicated to sky observation. The detector is formed by three 2048 \(\times\) 4608 CCDs with 13.5 \(\mu\text{m}\) pixels, with a scale of 000973 pixel\(^{-1}\). The CCDs create a mosaic of 6144 \(\times\) 4608 pixels with a small gap between the chips of 37 columns.

Table 1 shows the observing log, indicating the instrumental setup, air mass, and exposure times, the dispersion, the final resolution, and the seeing (FWHM) of each observation. The data were reduced using the Gemini package version 1.8 inside IRAF.8 All science exposures, comparison lamps, and spectroscopic twilight and GCAL flats were overscan/bias subtracted and trimmed. The spectroscopic GCAL flats were processed by removing the calibration unit plus GMOS spectral response and the calibration unit uneven illumination. Twilight flats were used to correct for the illumination pattern in the GCAL lamp flat using the task gresponse in the GMOS package. The twilight spectra were divided by the response map obtained from the lamp flats and the resulting spectra were averaged in the dispersion direction, giving the ratio of sky to lamp response for each fiber. The final response maps were obtained then by multiplying the GCAL lamp flat by the derived ratio. The resulting extracted spectra were then wavelength calibrated, corrected by the relative fiber throughputs, and extracted. The residual values in the wavelength solution for 60–70 points using a fourth or fifth Chebyshev polynomial typically yielded r.m.s values of \(\sim 0.10\, \text{Å}\) and \(\sim 0.15\, \text{Å}\) for both gratings, respectively. The final spectra cover a wavelength interval of \(\sim 3021\)–5823 \(\AA\) and \(\sim 4371\)–7225 \(\AA\) for data taken.

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8 IRAF is distributed by NOAO, which is operated by the Association of Universities for Research in Astronomy Inc., under cooperative agreement with the National Science Foundation.
Table 1
Observational Setup

| Grating | Central Wavelength (Å) | Air Mass | Exposure Time (s) | Resolution (Å) | Dispersion (Å/pixel) | Seeing (") |
|---------|------------------------|----------|-------------------|----------------|----------------------|------------|
| B600    | 4300                   | 1.24     | 1 × 1800          | 1.98           | 0.45                 | 0.8        |
| R600    | 5850                   | 1.47     | 2 × 2000          | 1.67           | 0.47                 | 0.9        |

Figure 2. One-dimensional blue and red parts of the spectrum, obtained as the sum of all fibers, in the rest-frame wavelength. In this figure, only the lines used in the analysis are indicated.

The flux calibration was performed using the sensitive function derived from observation of the star LTT 3864 for both gratings on December 31 and January 1. Standard stars were not observed in August. Therefore, the blue part of the spectra was constructed using only the observation obtained in 2004 December. The two-dimensional data images were transformed into a three-dimensional data cube ($x$, $y$, $\lambda$) using the gcube routine and resampled as square pixels with 0.1 of spatial resolution. The emission line fluxes were measured using the IRAF task fitprofs by fitting Gaussian profiles. From these, we then created the emission line maps used in our analysis (see Section 3).

At shorter wavelengths the IFU spectroscopy and long-slit observations suffer a spatial translation produced by differential atmospheric refraction (DAR). This effect is wavelength dependent, and is produced by the deviation of the light when it passes through the atmosphere due to the variation of the air density as a function of elevation. In order to obtain fluxes corrected for DAR, we used a similar procedure as described in Arribas et al. (1999) and also applied by Westmoquette et al. (2007a).

First, we split the data cube in monochromatic images, and for each image we calculated the centroid of an unresolved point source in the field of view that in our case corresponds to region A. Finally, the various monochromatic maps were aligned by shifting the centroids to the same position.

In Figure 2, we show the resultant spectrum for the two gratings used, obtained from the sum of all GMOS–IFU fibers. Figure 3 shows a detailed view of the selected emission lines considered in this study. The spectral resolution of the GMOS–IFU observations allows us to resolve the [O ii] $\lambda$ 3726,29 doublet lines in a limited number of apertures with a $\Delta \lambda = 2.32$ Å between the peak of the lines in the integrated spectrum (see Figure 3). The low intensity of [O ii] $\lambda$ 3726,29 lines and [O iii] $\lambda$ 4363 are the largest sources of uncertainties in our results. An automatic procedure to measure these emission line fluxes was not possible, therefore these lines were measured manually using splot.

3. RESULTS

3.1. Emission Line, Continuum, and EW(H$\beta$) Maps

We used a flux measurement procedure described in the previous section to produce the maps for the following emission lines: [S ii] $\lambda$ 6731, [S ii] $\lambda$ 6717, [N ii] $\lambda$ 6584, H$\alpha$, [O iii] $\lambda$ 5007, [O iii] $\lambda$ 4959, H$\beta$, [O iii] $\lambda$ 4363, H$\gamma$, [O ii] $\lambda$ 3726,29, H$\delta$ and H$\beta$ continuum, and EW(H$\beta$), in a rectangular field of 3" × 4.5" (see Figure 1). In order to reduce the number of data points without losing spatial information and signal-to-noise ratio (S/N), the data were resampled to 0.02 in spatial resolution. Typical S/N for individual pixels (spaxels in our data cube) for [O ii] $\lambda$ 5007 are $\gtrsim$ 700 and $\gtrsim$ 500 for regions A and B, respectively. The [O iii] $\lambda$ 4363 line shows a typical S/N $\gtrsim$ 8 and $\gtrsim$ 4 for regions A and B, respectively. The S/N for each emission line is given by the ratio between the emission line peak and the rms of the adjacent continuum. Figure 4 shows some of the observed emission line maps. All emission and continuum maps in this figure are in units of $10^{-18}$ erg cm$^{-2}$ s$^{-1}$, except for the H$\beta$ equivalent width map, which is in units of Å. Here 0.2 $\approx$ 50 pc (distances in this work were computed assuming a Hubble constant of $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$). Since most of the emission lines were measured using an automatic procedure, we filtered the maps assigning the value 0 erg cm$^{-2}$ s$^{-1}$ to all pixels with S/N $< 3$.

The maps in Figure 4 show essentially the same spatial distribution, presenting two well defined and regular regions, that we have labeled A and B. The maximum peak intensity of...
Figure 3. Subsets from the spectra in Figure 2 showing details of selected emission lines considered in this study.

the Hα emission line in region A is indicated in the maps by a × symbol. The recombination lines Hα, Hβ, and Hγ have very similar spatial distribution to the forbidden lines in Figure 4, but there is a slight difference in the spatial distribution of [O iii]λ4363 and [O ii]λλ3726,29 over region B. The last two images in Figure 4 corresponds to the spatial distribution of the Hβ continuum and the EW(Hβ), respectively. It is clear from the maps that the continuum peak is not coincident with the maximum in Hα emission. This has been previously reported by other authors (e.g., Sargent & Filippenko 1991; Maiz-Apellaniz et al. 1998; Lagos et al. 2007) in some galaxies with single and multiple star-forming regions. In NGC 4214, Sargent & Filippenko (1991) and Maiz-Apellaniz et al. (1998) found that the continuum peak emission was displaced in relation to the line emitting regions where a strong W–R feature (HeII λ4686 Å) was also seen. No W–R signatures were detected in the spectra of UM 408.

The largest EW(Hβ) values in the galaxy are associated with region A, indicating that this region is younger than region B. On the other hand, the Hβ continuum map (see Figure 4) shows the largest values over region B. In Section 4, the EW(Hβ) values are used as a proxy for the starburst ages in order to derive the integrated physical properties of the galaxy and their star-forming regions. The error associated with each emission line (σi) was calculated using the relationship given in Castellanos et al. (2002)

\[ \sigma_i = \sigma_c N^{1/2} \sqrt{1 + \frac{\text{EW}}{N \Delta}} \]  

where σc is the standard deviation in the local continuum associated with each emission line, N is the number of pixels, EW is the equivalent width of the line, and Δ is the instrumental dispersion in Å (see Table 1). These estimated errors will be used later in the derivation of uncertainties in the oxygen abundance determination and integrated properties.

Finally, given that the seeing was 0′′.8–0′′.9 (≈4 pixels in the emission line maps), each aperture or pixel of 0′′.2 should be correlated with its neighbor, and the pixel-to-pixel variations in the maps produced from the observed emission line are likely due to the uncertainties attached to the measurement and do not represent real variations. Therefore, we smoothed the emission line ratio, temperature, and oxygen abundance maps using a 3×3 box.

3.2. Extinction

The logarithmic reddening parameter c(Hβ) was calculated from the ratio Hα/Hβ, where the intrinsic value of 2.87 for case B recombination was assumed. Thus, the corrected emission
Figure 4. Observed maps for [S ii] λ6717, [N ii] λ6584, Hα, [O iii] λ5007, [O iii] λλ3726, 29 emission lines, Hβ continuum, and EW(Hβ). Fluxes in units of $\times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ and EW(Hβ) in units of Å. Hα emission line contours are overplotted on all maps. The maximum Hα emission is placed over region A and is indicated in the maps by a $\times$ symbol. The regions in the [O iii] λ5007 map mark the areas considered as regions A and B.

(A color version of this figure is available in the online journal.)

lines are calculated as

$$\frac{I(\lambda)}{I(H\beta)} = \frac{F(\lambda)}{F(H\beta)} \times 10^{c(H\beta)f(\lambda)},$$

where $I(\lambda)$ and $F(\lambda)$ are the dereddened flux and observed flux at a given wavelength, respectively, and $f(\lambda)$ is the reddening function given by Seaton (1979) as parameterized by Howarth (1983), using appropriated values for the Milky Way (Kobulnicky et al. 1997).
The standard BPT diagnostic diagrams (Baldwin et al. 1981) have been used to analyze the possible excitation mechanisms present in UM 408. Figure 6(a)–(c) shows the following emission line ratio maps: \([\text{[O III]}]/\lambda5007/\text{H}β\) (\([\text{O III]}]/\text{H}β\), \([\text{S II]}]/\lambda6717,6731/\text{H}α\) (\([\text{S II]}]/\text{H}α\)), and \([\text{[N II]}]/\lambda6584/\text{H}α\) (\([\text{[N II]}]/\text{H}α\)). Figure 6 shows that \([\text{O III]}]/\text{H}β\) and \([\text{S II]}]/\text{H}α\) ratios have essentially the same spatial distribution with inverse trends. The largest values of \([\text{O III]}]/\text{H}β\) and the lowest values of \([\text{S II]}]/\text{H}α\) are seen in the east part of the galaxy, near region B. The emission line ratios measured within these regions are common to high excitation \(\text{H}II\) regions with values ranging from \(\log([\text{O III]}]/\text{H}β) = 0.45\) to \(0.80\) (all map), \(0.65\) to \(0.76\) (region A), and \(0.72\) to \(0.80\) (region B), and from \(\log([\text{S II]}]/\text{H}α) = −0.62\) (all map), −1.17 to −0.85 (region A), and −1.21 to −1.01 (region B). Additionally, the low ionization ratios \([\text{N II]}]/\text{H}α\) and \([\text{S II]}]/\text{H}α\) increase from the center outwards.

Figure 7 divides the diagram into two regions that correspond to line ratios explained solely by photoionization by massive stars and to line ratios where an additional source of excitation must be present, as in the case of active galactic nuclei (AGNs; Osterbrock & Ferland 2006). From the distribution of the data in the diagnostic diagram we conclude that the \(\text{H}II\) regions in UM 408 are produced by photoionization by massive stars.

3.4. Density, Temperature, and Oxygen Abundance

The first step in the abundance derivation is to obtain the electron density and temperature. The electron density is obtained using the emission line ratio \([\text{S II]}]/\lambda6717/[\text{S II]}]/\lambda6731\), and the electron temperature from the ratio \([\text{O III]}]/\lambda4959,5007/[\text{O III]}]/\lambda4363\). In Figure 8(a), we can see that the ratio \([\text{S II]}]/\lambda6717,6731\) is typically greater than 1 which indicates a low density regime (Osterbrock & Ferland 2006), hence, we assumed an electron density of \(n_e \sim 100\) \(\text{cm}^{-3}\) for all apertures in our calculations. To obtain the electron temperature \(T_e(\text{O III})\) we used the five level atomic model FIVEL (De Robertis et al. 1987), implemented under the IRAF STS package NEBULAR. This program has been developed to obtain the physical conditions in a low-density nebula, given appropriate emission line ratios. Figure 8(b) shows the \([\text{[O III]}]/\lambda4959,5007/[\text{O III]}]/\lambda4363\) emission line ratio used to calculate the electron temperature \(T_e(\text{O III})\), and Figure 8(c) shows the resulting spatial distribution of electron temperature \(T_e(\text{O III})\). The range of valid data points varies from \((1.20–1.70) \times 10^4\) \(\text{K}\) with a standard deviation of \(0.1 \times 10^4\) \(\text{K}\) for the original data set and from \(1.37\) to \(1.53\) \(\times 10^4\) \(\text{K}\) with a standard deviation of \(0.03 \times 10^4\) \(\text{K}\) for the smoothed data points. The total oxygen abundances for each aperture are assumed to constitute the sum of \(O^+\) and \(O^{++}\) ions, thus we have that

\[
\frac{O}{H} = \frac{O^+}{H^+} + \frac{O^{++}}{H^+},
\]

where the \(T_e(\text{O III})\) temperature and the \(O^+\) and \(O^{++}\) ions are obtained assuming the expressions given by Pagel et al. (1992). Figure 9(a) shows the spatial distribution of the oxygen abundances over the regions where the emission line \([\text{O III]}]/\lambda4363\) was detected. The oxygen abundance values in units of \(12 + \log(O/\text{H})\) range from \(7.70 \pm 0.08\) to \(7.84 \pm 0.04\) with a maximum error of \(\sim 0.12\) dex, an average value of \(7.77\) and a standard deviation of \(0.10\) dex. However, the smoothed map has values from \(7.69\) to \(7.86\) with a standard deviation of \(\sim 0.04\) dex.
Figure 6. Emission line ratios: (a) log \([\text{O}^\text{III}]\lambda 5007/\text{H}\beta\), (b) log \([\text{S}^\text{II}]\lambda \lambda 6717,6731/\text{H}\alpha\) and (c) log \([\text{N}^\text{II}]\lambda 6584/\text{H}\alpha\). The maximum \(\text{H}\alpha\) emission is placed over region A and is indicated in the maps by an X symbol. \(\text{H}\alpha\) contours are overplotted on Figure (a).

Figure 7. \([\text{O}^\text{III}]/\text{H}\beta\) vs. \([\text{S}^\text{II}]/\text{H}\alpha\) diagnostic diagram for the original data points presented in Figure 6(a) and (c). The red crosses correspond to region A, the green crosses to region B, and the black crosses to the outer part of the galaxy. The integrated value for the galaxy is represented by the blue star. The solid line is the dividing line between \(\text{H}^\text{II}\) galaxies and AGNs (Osterbrock & Ferland 2006).

Figure 9(b) shows the radial distribution of oxygen abundance with respect to the \(\text{H}\alpha\) peak emission within a region \(\lesssim 0.4\) kpc. Statistically the bulk of the original data points are lying in a region of \(\pm 2\sigma\) dispersion (\(\sigma = 0.1\) dex) around the average value. The \(2\sigma\) dispersion is represented by the dotted lines. A least-fit square with a slope of \(-0.14 \pm 0.06\) dex kpc\(^{-1}\) was found, using all original data points in Figure 9(b). The error in the gradient is obtained directly from the linear regression. In the same figure, we show the radial distribution of the smoothed data points as light blue triangles. These results indicate that there is no significant variations across the galaxy. At most, we can say that there is a very marginal gradient of a decreasing abundance from the center outward, indicating that, on average, the highest abundance values are found near the peak \(\text{H}\alpha\) emission.

3.5. Velocity Field

The internal structure of \(\text{H}^\text{II}\) galaxies and GHIIRs, as viewed in the ionized gas, is directly associated with mechanisms of photoionization, magnetic field induced turbulence, and feedback by the current episode of massive star formation and evolution, i.e., radiative shocks, stellar and SNe driven winds. All of it, under the influence of the gravitational potential of the complex of gas and stars. The presence of expanding structures (shells, loops, and bubbles) is very common in GHIIRs (e.g., the Hubble Space Telescope (HST) image on NGC 604, Tenorio-Tagle et al. 2000; Chu & Kennicutt 1994, for 30 Doradus). These structures have also been observed in the prototypical \(\text{H}^\text{II}\) galaxies as II Zw 40 and their resulting nested filaments have been explained by the effects of photoionization and stellar winds in an inhomogeneous ISM (Tenorio-Tagle et al. 2006). UM 408 shows, in the \(\text{H}\alpha\) emission line map (Figure 4) and in the acquisition broadband image (Figure 1), an outer regular shape with no signs of large-scale disruption or a galactic wind (see Westmoquette et al. 2007b, and references therein for the case of NGC 1569). The monochromatic maps, presented in this study, do not provide clear evidence of expanding structures, shell-like features or filaments.

In order to study the impact of the star formation on its internal kinematic properties, we derived the spatial distribution of radial velocity \(v_r\) (heliocentric) and velocity dispersion \(\sigma\) (FWHM/2.355) by fitting a single Gaussian to the \(\text{H}\alpha\) emission line profiles. Figure 10 shows the radial velocity derived from the shifts of the \(\text{H}\alpha\) line peak, and dispersion velocity maps calculated by using the following relation:

\[
\sigma^2(\text{H}\alpha) = \sigma^2_{\text{obs}} - \sigma^2_{\text{inst}} - \sigma^2_{\text{th}},
\]

where \(\sigma_{\text{obs}}\) is the observed \(\text{H}\alpha\) velocity dispersion, \(\sigma_{\text{inst}}\) is the instrumental dispersion, and \(\sigma_{\text{th}}\) is a correction for thermal broadening (\(\sqrt{\kappa T_e/m_H} \approx 9.1\) km s\(^{-1}\) for hydrogen at a temperature of \(T_e = 10^4\) K). We have used a value of \(33.4 \pm 1.0\) km s\(^{-1}\) for the instrumental dispersion by comparing the nominal value (from Table 1) with that measured directly from the calibration lamps in the grim R600 near \(\text{H}\alpha\), and assigning the error as the rms of the average.

The velocity field (Figure 10(a)) shows an apparent systemic motion where the east part of the galaxy (near knot B) is
blueshifted, while the west part (near knot A) is redshifted, with a relative motion of \( \sim 10 \) km s\(^{-1} \). This motion may contribute to broaden the integrated line profile over the extent of the whole galaxy. However, it is not enough to explain the total integrated supersonic line width observed of \( \sigma = 18.6 \pm 1.5 \) km s\(^{-1} \).

Figure 10(b) shows the velocity dispersion (line width) map over the observed field, ranging values from \( \sim 10 \) km s\(^{-1} \) to \( \sim 30 \) km s\(^{-1} \). The velocity dispersion varies little across the field, but some points are worth noting. This map is characterized by a subsonic area near region A, while the highest values are located in the outer part of the field of view near region B. The 1 pixel line width over knot A (the brightest region) has a low \( \sigma \) of 17.1 \( \pm \) 1.0 km s\(^{-1} \). This value is identical to a synthetic aperture of 2.7 over knot A. This synthetic aperture was chosen
to mimic the single fiber high-dispersion observation of Bordalo (2004) who find $\sigma = 19.6 \pm 0.4$ km s$^{-1}$ that is consistent with our results.

4. DISCUSSION

4.1. The Integrated Properties of UM 408

We have measured the flux in two different apertures enclosing more than $\sim60\%$ of the observed H$\alpha$ flux of the galaxy in order to study the properties of the star formation regions detected in this galaxy. One aperture for region A (48\% of the measured H$\alpha$ flux) and another for region B (13\% of the measured H$\alpha$ flux). These regions have diameters of about 1′′ and 1″ that correspond to approximately 375 pc and 250 pc, respectively. Regions A and B are indicated in the [O iii] $\lambda$5007 map of Figure 4. These regions are formed by the data points where [O iii] $\lambda$4363 emission was measured. Columns 4 and 5: regions defined in Figure 4.

Table 2

| Line          | Integrated Galaxy | [O iii] $\lambda$4363 Measured | Region A | Region B |
|---------------|-------------------|---------------------------------|----------|----------|
| [S ii] $\lambda$6731 | 0.24 $\pm$ 0.01   | 0.20 $\pm$ 0.03                 | 0.20 $\pm$ 0.03 | 0.20 $\pm$ 0.04 |
| [S ii] $\lambda$6717  | 0.32 $\pm$ 0.01   | 0.28 $\pm$ 0.04                 | 0.27 $\pm$ 0.03 | 0.27 $\pm$ 0.04 |
| [N ii] $\lambda$6584  | 0.13 $\pm$ 0.01   | 0.11 $\pm$ 0.03                 | 0.11 $\pm$ 0.02 | 0.10 $\pm$ 0.03 |
| H$\alpha$          | 5.94 $\pm$ 0.07   | 6.07 $\pm$ 0.29                 | 6.14 $\pm$ 0.28 | 5.87 $\pm$ 0.28 |
| [O iii] $\lambda$5007 | 5.24 $\pm$ 0.21   | 5.33 $\pm$ 0.30                 | 5.30 $\pm$ 0.25 | 5.60 $\pm$ 0.36 |
| [O iii] $\lambda$4959 | 1.71 $\pm$ 0.18   | 1.72 $\pm$ 0.11                 | 1.71 $\pm$ 0.11 | 1.80 $\pm$ 0.11 |
| [O iii] $\lambda$4363 | 0.06 $\pm$ 0.01   | 0.07 $\pm$ 0.01                 | 0.07 $\pm$ 0.01 | 0.07 $\pm$ 0.02 |
| H$\beta$           | 0.29 $\pm$ 0.01   | 0.31 $\pm$ 0.04                 | 0.31 $\pm$ 0.04 | 0.36 $\pm$ 0.05 |
| [O ii] $\lambda$3726,29 | 0.52 $\pm$ 0.17   | 0.30 $\pm$ 0.05                 | 0.32 $\pm$ 0.04 | 0.27 $\pm$ 0.05 |
| F(H$\beta$)         | 39.70 $\pm$ 0.20  | 24.93 $\pm$ 0.86                | 18.63 $\pm$ 0.62 | 5.09 $\pm$ 0.17 |

Notes. Fluxes normalized to F(H$\beta$) in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. Column 2: integrated galaxy corresponds with the values obtained from the sum of all spaxels in the data cube. Column 3: [O iii] $\lambda$4363 measured corresponds with sum of all apertures in the maps where [O iii] $\lambda$4363 was measured. Columns 4 and 5: regions defined in Figure 4.
Table 3

| Parameter | Integrated Galaxy | [OIII]λ4363 Measured | Region A | Region B |
|-----------|-------------------|----------------------|---------|---------|
| (1)       | (2)               | (3)                  | (4)     | (5)     |
| ε(Hβ)     | 0.93 ± 0.02       | 0.96 ± 0.06          | 0.97 ± 0.06 | 0.91 ± 0.06 |
| T_e(OIII) × 10^4 (K) | 1.40 ± 0.08 | 1.45 ± 0.14          | 1.45 ± 0.12 | 1.44 ± 0.16 |
| T_e(OII) × 10^4 (K) | 1.32 ± 0.11 | 1.34 ± 0.18          | 1.34 ± 0.16 | 1.34 ± 0.21 |
| n_e (cm^-3) | ~100            | ~100                 | ~100     | ~100     |
| log(OIII)λ5007/Hβ | 0.69 ± 0.02       | 0.70 ± 0.02          | 0.69 ± 0.02 | 0.72 ± 0.03 |
| [S II]λ3371/Hα | 0.09 ± 0.01       | 0.08 ± 0.01          | 0.07 ± 0.01 | 0.08 ± 0.02 |
| O/H×10^5   | 1.16 ± 0.26       | 0.64 ± 0.09          | 0.70 ± 0.09 | 0.57 ± 0.10 |
| O/C×10^5   | 6.35 ± 0.58       | 5.88 ± 0.68          | 5.85 ± 0.60 | 6.31 ± 0.82 |
| 12+log(O/H) | 7.87 ± 0.05       | 7.81 ± 0.05          | 7.82 ± 0.05 | 7.84 ± 0.06 |
| log L(Hα) (erg s^-1) | 39.47 | 39.27 | 39.15 | 38.58 |
| log (number of photons) (photons s^-1)^a | 51.34 | 51.14 | 51.01 | 50.45 |
| SFR(M⊙ yr^-1)^a | 0.024 | 0.015 | 0.011 | 0.003 |
| EW(Hβ) (Å) | 62 | 89 | 102 | 57 |
| Age (Myr)^b | ... | 4.73 | 4.83 | 5.00 |

Notes.

a Number of photons and SFR were obtained using the relations given by Kennicutt (1998).
b Ages were obtained using the STARBURST99 predictions model, assuming an instantaneous star formation and a Salpeter IMF from 1 to 100 M⊙.

derived with slit spectroscopy (e.g., Terlevich et al. 1991; Masegosa et al. 1994; Pustilnik et al. 2002) considering aperture differences and observational uncertainties. A larger discrepancy however occurs between our observed [O III]λ5007,29/Hβ value of 0.52 and that of Pustilnik et al. (2002) of 1.45. However, their value must be overestimated since, from their Figure 1, we clearly see that Hβ > [O III]λ3727.

The observed EW(Hβ) values in UM 408 are ~102 Å and ~57 Å for regions A and B and ~67 Å for the integrated galaxy, respectively. The values for regions A and B have been calculated by taking the average over all pixels in each region. Using these EW(Hβ) values we can estimate the cluster ages by comparison with the values obtained from STARBURST99 model (Leitherer et al. 1999). The resulting ages assuming an instantaneous burst and a metallicity of Z = 0.004 for a Salpeter initial mass function (IMF) with a mass limit of 1–100 M⊙ are 4.83 Myr and 5.00 Myr for regions A and B, respectively. These ages are consistent with both regions being formed simultaneously. We found integrated luminosities (assuming a distance of D = 46.8 Mpc; Pustilnik et al. 2002) of log L(Hα) = 39.15, 38.58, and 39.47 erg s^-1 for regions A and B and for the integrated galaxy, respectively. These correspond to a star formation rate of SFR = 0.011, 0.003, and 0.024 M⊙ yr^-1, and with a number of ionizing photons log Q(Hβ) = 51.01, 50.45, and 51.34 photons s^-1 for regions A, B, and for the integrated galaxy, obtained from the relationships given by Kennicutt (1998). The masses of these regions can be estimated by scaling the number of ionizing photons with the models predicted for the corresponding ages. The stellar masses are 5.17 × 10^4 M⊙ and 2.29 × 10^4 M⊙ for regions A and B, respectively. Table 3 shows the derived integrated properties of the galaxy and its star-forming regions.

Since its discovery, UM 408 was classified as a low-abundance galaxy with an integrated value of 12+log(O/H) = 7.63 for low-resolution spectroscopy (Masegosa et al. 1994) and 7.93 for high-resolution spectroscopy (Pustilnik et al. 2002). In this work, we found an integrated abundance (summing over all spaxels in our field of view) of 12+log(O/H) = 7.87 ± 0.05. The synthetic apertures previously mentioned yield an Integrated Oxygen abundance of 12+log(O/H) = 7.82 ± 0.05 and 7.84 ± 0.06 for regions A and B, respectively. Measuring the abundance in an aperture equivalent with the area where the emission line [O III]λ4363 was measured we obtain a value of 7.81 ± 0.05, the same value obtained in the peak of the Hα emission (see Figure 9(b)). This result reflects the fact that the integrated values are light weighted and dominated by the galaxy peak emission.

Finally, despite the fact that a detailed kinematic analysis is beyond the scope of the present paper, our results confirm that the core dominates the kinematic information of the star-forming region, and present a low a value, as found by other works (e.g., Telles et al. 2001, and references therein). Therefore, a single Gaussian fit to the line profile of any aperture encompassing the brightest knot will measure a representative line width of the dominant supersonic motions, somewhat deconvolved by the effects of stellar and SN mechanical energy input. The effects of stellar or SN feedback will contribute to the broadening of the line profiles, but will only be detectable in the lower density regions at low intensities. One means to recognize these effects is through the identification of inclined bands in the diagnostic diagrams of intensity versus a (e.g., as proposed by Muñoz-Tuñón et al. 1996) and Yang et al. (1996). However, the compactness of UM 408 and the small range of reliable line widths make the use of the diagnostic diagrams difficult to interpret in this case. The Hα line profile is symmetric and well represented by a single Gaussian, and does not show prominent low intensity wings in either apertures. An attempt to deblend a possible additional component to this line profile produced only an upper limit of σbroad < 100 km s^-1 with F(σbroad)/F(σnarrow) ≤ 3%.

4.2. Distribution of the Oxygen Abundance and Their Comparison with Other Dwarf Galaxies

The uniform behavior of O/H abundance in scales of hundreds of pc in low-mass galaxies as in UM 408 is not without precedent, and is comparable with the observed variation in some dwarf galaxies by other authors. In NGC 4214 (dwarf irregular/W–R galaxy) Kobulnicky & Skillman (1996) showed...
that there is no localized O, N, or He abundance gradients, but they found, near the youngest region, an oxygen overabundance of 0.095 ± 0.019 dex. Kobulnicky & Skillman (1997), using long slit spectroscopy to study the ISM of the dwarf irregular galaxy NGC 1569, failed to find evidence for O/H gradient from the recent star formation activity. Lee et al. (2006) studied the local group dwarf irregular galaxy NGC 6822 and measured a difference of $\Delta(O/H) = 0.53$ dex between the maximum (8.43 ± 0.2) and minimum value (7.90 ± 0.1), with a mean oxygen abundance of 12+log(O/H) = 8.11 ± 0.1 using only the H II regions where the [O III]λ4363 emission lines were detected. A gradient of $-0.14 \pm 0.07$ dex kpc$^{-1}$ was measured by Lee et al. in a radius ≤1.4 kpc, and a slope of $-0.16$ dex kpc$^{-1}$ was obtained if measurements from the literature were included, showing the existence of a possible radial gradient in oxygen abundance. Izotov et al. (2006) using VLT/GIRAFFE in the ARGUS mode, observed the dwarf galaxy SBS 0335-052E, one of the most metal-poor galaxies with an integrated oxygen abundance of 12+log(O/H) = 7.30 (Melnick et al. 1992). The spatial distribution of the oxygen abundance in the ISM of SBS 0335-052E vary from 7.00 ± 0.82 to 7.42 ± 0.02, representing a difference of $\Delta(O/H) = 0.42$ dex. The maximum value of oxygen abundances in this galaxy does not correspond to the position of one of the identified SSCs, but Izotov et al. find a slight trend of a decreasing abundance, interpreted as possible self-enrichment. However, they argue that the errors in the calculated oxygen abundances and $T_e$, $n_e$, etc., not considering instrumental and observational uncertainties, lead to consider the oxygen abundance variations in SBS 0335-052E may not be statistically significant. More recently, using IFU-PMAS observations, Kehrig et al. (2008) studied the spatial distribution of some metals over the galaxy IIZw70. In this study, they find a difference of $\Delta(O/H) = 0.40$ dex between the maximum (8.05 ± 0.06) and minimum (7.65 ± 0.06) values of oxygen abundance. In the case of UM 408, the bulk of our observed data points are distributed in a region of ±2σ dispersion around the average value with a difference between the maximum and minimum values of 0.47 dex. This is, somewhat, in good agreement with previous results in other dwarf galaxies, using in some cases different techniques. We note that the gradient found in our work, calculated in a spatial scale of hundreds of pc, is similar to the gradients calculated in other studies in scales of kpc. Finally, the two giant regions A and B show a difference of oxygen abundance of only $\Delta(O/H) = 0.02$ dex, which indicates that these regions show identical chemical properties within the errors. Given the ages (~5 Myr) and stellar masses ($\sim 10^9 M_\odot$) of these regions, we expect that hundreds of SNe have exploded, producing eventually localized enrichments. But the absence of chemical overabundances in the ISM of UM 408 and in the dwarf galaxies studied in the literature leads to conclude that the population of young clusters have not produce preferentially localized overabundances.

These results are compatible with the interpretation that the newly synthesized metals from the current star formation episode may not be in the warm phase of the ISM, and thus are not observed at optical wavelengths. The metals that are observed, however, ought to be from previous events, and may be well mixed and homogeneously distributed over the whole extent of this low mass and compact galaxy. Note that in UM 408, there is no bar-induced rotation, or shear, to produce the metal dispersal and mixing as in more massive galaxies (e.g., Roy & Kunth 1995), and thus there must be another mechanism responsible for the large-scale dispersal and mixing with the ISM. One such hydrodynamic mechanism for the transport and mixing of the metals produced by compact bursts of star formation into the ISM has been proposed by Tenorio-Tagle (1996). This model predicts that the energy injected by core-collapse SNe change the physical conditions (density and temperature) of the interstellar medium, while undergoing a long excursion into the galactic volume. The injected matter is first thermalized, near the starburst, as it goes through a reverse shock. This generates the giant pressure that allows for the built up of superbubbles, kpc scale structures that may grow for up to 50 Myr. Afterwards, once the SN II phase is over, the giant superbubble gas begins to cool down by radiation. This happens first within the parcels of gas that present the largest densities, promoting their thermal instability. The sudden loss of pressure within the densest parcels of gas would immediately trigger the appearance of re-pressurizing shocks emanating from the low density hot gas. The process leads to a plethora of dense condensations that inevitably will fall and settle within the main body of the galaxy. The process of cooling and dispersal onto the main body of the galaxy will occur within a few $10^8$ yr. For a complete mixing, the model assumes that a further star formation episode has to occur and through photoionization the metal enriched condensations will expand and be fully mixed with the ISM (see also Stasinska et al. 2007). This scenario seems plausible and compatible with our analysis for the case of UM 408.

5. CONCLUSIONS

We used GMOS–IFU spectrum of the compact H II galaxy UM 408, in order to derive the spatial distribution of emission line ratios, extinction c(Hβ), radial velocity $v_r$, velocity dispersion $\sigma$, electron temperature, and oxygen abundance (O/H) as well the integrated properties over an extended region of $3'' \times 4.4$ equivalent to 750 pc × 1100 pc in the central part of the galaxy. Below, we summarize our results and conclusions.

1. The observed region of the galaxy includes two giant H II regions not resolved in previous studied, here labeled A and B. The sizes of these ionized regions are ∼375 and ∼250 pc for regions A and B, respectively. Another region labeled C was found to the east of region B. We do not observe large-scale structures as in other GHIIRs and H II galaxies in the monochromatic maps.

2. The distribution of dust content in the galaxy was derived from the Balmer line decrement (Hα/Hβ). The c(Hβ) distribution concentrates the highest values close but not coincident with the peak of Hα emission in each ionized cluster (A and B). The dust seems to be displaced from the star formation regions by the action of the star cluster winds.

3. We used [O iii]/Hβ and [S ii]/Hα ratios to investigate the possible excitation mechanism over the ISM of the galaxy. Comparing the data points in the diagnostic diagram with the theoretical model given by Osterbrock & Ferland (2006), we found that all measured Hα flux arises from gas photoionized by massive stars.

4. The velocity field ($v_r$) shows an apparent systemic motion where the east part of the galaxy (near knot B) is blueshifted, while the west part (near knot A) is redshifted, with a relative motion of ∼10 km s$^{-1}$ and a difference between the maximum a minimum values of ∼33 km s$^{-1}$. The velocity dispersion map shows supersonic values, typical for extragalactic H II regions, ranging values from ∼10 km s$^{-1}$ to ∼30 km s$^{-1}$. 

LAGOS ET AL. / Vol. 137
5. The ages of the two giant regions detected in this study were estimated from their EW(Hβ) and the STARBURST99 models, suggesting that they are coeval events of \( \sim 5 \) Myr with stellar masses of \( \sim 10^4 M_\odot \). We see a marginal difference in the integrated oxygen abundance between these regions of \( \Delta(O/H) = 0.02 \) dex.

6. Finally, as found in other nearby dwarf galaxies, we do not observe a gradient in oxygen abundance across the compact galaxy UM 408. The bulk of the observed data points are lying in a region of \( \pm 2\sigma \) dispersion (\( \sigma = 0.1 \) dex); therefore, the new metals formed in the current star formation episodes are not observed and reside probably in the hot gas phase (\( T \sim 10^7 \) K), whereas the metals from previous star formation events are well mixed and homogeneously distributed through the whole extent of the galaxy.

All results presented here are suggestive that UM 408 is an unevolved low-metallicity dwarf galaxy, undergoing a simultaneous episode of star formation over the whole optically observed extension, and it is a genuine example of the simplest starbursts occurring in galactic scale, possibly mimicking the properties one expects for young galaxies at high redshift.

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