A Headless Tadpole Galaxy: The High Gas-phase Metallicity of the Ultra-diffuse Galaxy UGC 2162

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Abstract

The cosmological numerical simulations tell us that accretion of external metal-poor gas drives star formation (SF) in galaxy disks. One the best pieces of observational evidence supporting this prediction is the existence of low-metallicity star-forming regions in relatively high-metallicity host galaxies. The SF is thought to be fed by metal-poor gas recently accreted. Since the gas accretion is stochastic, there should be galaxies with all the properties of a host but without the low-metallicity starburst. These galaxies have not been identified yet. The exception may be UGC 2162, a nearby ultra-diffuse galaxy (UDG) that combines low surface brightness and relatively high metallicity. We confirm the high metallicity of UGC 2162 $(12 + \log(O/H) = 8.52^{+0.21}_{-0.22})$ using spectra taken with the 10 m GTC telescope. UGC 2162 has the stellar mass, metallicity, and star formation rate surface density expected for a host galaxy in between outbursts. This fact suggests a physical connection between some UDGs and metal-poor galaxies, which may be the same type of object in a different phase of the SF cycle. UGC 2162 is a high-metallicity outlier of the mass–metallicity relation, a property shared by the few UDGs with known gas-phase metallicity.

Key words: galaxies: abundances – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: star formation – intergalactic medium

1. Scientific Rationale

Current cosmological numerical simulations predict that accretion of metal-poor gas from the cosmic web drives star formation in galaxy disks (e.g., Sancisi et al. 2008; Dekel et al. 2009; Silk & Mamon 2012; Sánchez Almeida et al. 2014). One of the best pieces of observational evidence in favor of this external feeding is the existence of low-metallicity star-forming regions in relatively high-metallicity host galaxies (Sánchez Almeida et al. 2013, 2015). The main low-metallicity starburst tends to be off-centered, so the galaxies commonly have a cometary or tadpole morphology (Papaderos et al. 2008; Morales-Luis et al. 2011). In terms of their average metallicity, these galaxies are often extremely metal-poor (XMP), with a light-weighted mean gas-phase metallicity smaller than a tenth of the value in the Sun $(Z_g < Z_{\odot}/10)$. Their starbursts are thought to be fed by metal-poor gas recently accreted by the galaxy, a process that has been recently modeled by Verbeke et al. (2014) and Ceverino et al. (2016). The galaxies hosting the XMP starburst are low surface brightness galaxies with a metallicity around half the solar metallicity $(Z_g \sim Z_{\odot}/2$; Sánchez Almeida et al. 2015). We will call them host galaxies. Since the gas accretion process is stochastic, there should be galaxies with the properties of the host galaxies, i.e., relatively high metallicity for their mass, low surface brightness, and without the bright low-metallicity star-forming region (i.e., headless tadpole galaxies). However, such galaxies have not been identified before. Low surface brightness galaxies are also faint galaxies (e.g., Skillman 1999), which, according to the luminosity–metallicity relation (e.g., Berg et al. 2012), are metal-poor. Actually, a few known low surface brightness dwarf galaxies with mean metallicity determined through the direct-method (DM; details in Section 2.2) seem to be XMP (e.g., Leo P by Skillman et al. 2013; Leoncino Dwarf by Hirschauer et al. 2016; and Little Cub by Hsyu et al. 2017).

UGC 2162 may be an exception compared to these low surface brightness dwarf galaxies with known metallicity, and so, it may be the sought-after headless tadpole galaxy that provides support to the whole picture. It may be one of the expected host galaxies, without a metal-poor starburst. It has been recently identified as a nearby low-mass UDG8 by Trujillo et al. (2017), with $M_* \sim 2 \times 10^7 M_{\odot}$, $M_{HI}/M_* \sim 10$, and $M_{dyn}/M_* \sim 200$ ($M_*, M_{HI}$, and $M_{dyn}$ stand for the stellar mass, the H I mass, and the dynamical mass, respectively). With an effective radius of 1.7 kpc, its g-band central surface brightness is 24.4 mag arcsec$^{-2}$. The galaxy is irregular with several bluish star-forming knots (Figure 1). UGC 2162 belongs to the group of M77, even though it is quite far from...
the central galaxy (293 ± 40 kpc projected distance; Trujillo et al. 2017). One of these knots has a spectrum in the Sloan Digital Sky Survey Data (SDSS-DR12; Alam et al. 2015). Using the line ratio N2 ([N II]λ6583/Hα) derived from the SDSS spectrum, and the calibration by Pettini & Pagel (2004), Trujillo et al. (2017) estimate an oxygen abundance for the star-forming ionized gas of 12 + log(O/H) = 8.22 ± 0.07, which corresponds to one-third of the solar abundance. If this metallicity estimate is correct, the gas of UGC 2162 is of high metallicity for its mass and magnitude, in the vein expected for the host galaxies having XMP star-forming regions. The reported high metallicity of UGC 2162 rests only on the low signal-to-noise ratio (S/N) SDSS spectrum, and on the estimate of its metallicity using N2. Due to the importance of the gas-phase metallicity of this particular galaxy, we obtained long-slit spectra of UGC 2162 with the 10 m GTC telescope, with enough wavelength coverage and S/N to carry out an independent robust determination of the gas-phase metallicity. The analysis of these spectra confirms the high metallicity of the star-forming gas in UGC 2162 (Section 2). The purpose of this paper is to present this determination and to show that UGC 2162 shares many properties in common with those expected for the host galaxies having XMP star-forming regions (Section 3). There seem to be a few other objects in the literature with the characteristics of UGC 2162. Discussions are included in Section 4.

9 With 12 + log(O/H)0 = 8.69, from Asplund et al. (2009).
10 Here and throughout the paper, we use the term XMP galaxy to denote a host galaxy plus one or a few metal-poor starbursts that outshine the emission-line spectrum of the host, so that the light-weighted average metallicity of the combined system is smaller than a tenth of the solar metallicity.

2. Observations and Metallicity Determination

2.1. Observations

We obtained long-slit spectra of UGC 2162 integrating for 2 hr with the instrument OSIRIS at the 10 m GTC telescope. The 1 arcsec wide slit was placed as shown in Figure 1, inclined with respect to the major axis so as to cover the two main star-forming regions of the galaxy and the diffuse emission around them. The resulting visible spectra span from 3600 to 7200 Å with a spectral resolution around 550, thus covering the wavelength range containing [O II]λ3727 and the temperature-sensitive line [O III]λ4363. The raw data were reduced following the usual procedure, which includes correction for bias and flat-field, and flux and wavelength calibration. We employ PyRAF12 for the task. Figure 2 shows one of the resulting spectra, corresponding to the brightest knot of the galaxy (the southern-most knot in Figure 1). The slit was not oriented along the parallactic angle, however, differential refraction is not an issue since the airmass of observation is low (<1.2), and the residual effect is corrected for by the flux calibration.

2.2. Metallicity Determination

The DM is the method of reference to measure metallicities when all the required emission lines are available (e.g., Stasińska 2004; Pérez-Montero 2017). It obtains the physical properties of the emitting gas from the same spectrum used to determine the metallicity, minimizing the model dependence of the result. In the case of the oxygen abundance, the emission-line ratio [O III]λ4363/[O III]λ5007 is needed to determine the electron temperature of the nebulae and so to determine the oxygen abundance using the DM (e.g., Osterbrock 1974; Pérez-Montero 2017). As it happened with the SDSS spectrum analyzed by Trujillo et al. (2017), [O III]λ4363 does not show up above the noise level even in the GTC spectra. The two-dimensional (2D)
The spectral region around $H\alpha$ is presented as solid symbols whereas the red and the yellow lines stand for the full galaxy, two bright points, and the diffuse component. In terms of the distances represented in Figure 3(a), the full galaxy considers the average spectrum from $-21''$ to $+1''$, the first bright point from $-19''$ to $-15''$, the second bright point from $-8''$ to $-3''$, and the diffuse component from $-15''$ to $-6''$ (see also the ticks in Figure 1). Thus, the spectra of the two bright points and the diffuse component come from different parts of UGC 2162, whereas the full galaxy spectrum basically averages the three of them. In all four cases the metallicity is relatively high, with $12 + \log(O/H)$ between 8.3 and 8.7 (Table 2, column 1). This range of values is within the error bar of the measurement, as we discuss in the next paragraph.

HCm provides formal error bars from the difference between the observed fluxes and those provided by the photoionization models. They are rather small ($< 0.1 \text{dex}$; see Table 2), and do not include the uncertainty associated with the non-detection of $[\text{O}\ III]\lambda4363$. In order to be conservative and include this other source of error, we developed an alternative way to evaluate the error bars of the measured abundances. We carried out a Monte-Carlo simulation where $[\text{O}\ III]\lambda4363$ was assumed to have a flux smaller than the upper limit set by the noise of the GTC spectra. Specifically, we assume $[\text{O}\ III]\lambda4363$ to be drawn from a uniform distribution consistent with the noise in the observation, with values going from zero to the value set by the Gaussian function fit to the noise shown in Figure 3(c). We drew 1000 random values, from which we compute the median and the 1σ error bar (i.e., the range of values in between percentiles 15.9% and 84.1%). The result for the brightest point is given in Table 2, column 2. The measurement, along with its error bar, provides the range of values of $12 + \log(O/H)$ consistent with the noise level of the GTC spectra. This range is consistent with the value inferred from a single application of HCm, except that the error bars are significantly larger. We repeated the same exercise with the metallicities inferred applying the DM.\(^{13}\) The result is given in Table 2, column 3. Once again, the result is consistent with the high metallicity inferred by Trujillo et al. (2017) from the SDSS spectrum. In the case of Trujillo et al. (2017), they used the line ratio $N_2([\text{N}\ II]\lambda6583/\text{H}\alpha)$ to estimate $12 + \log(O/H)$ as calibrated by Pettini & Pagel (2004). We have repeated the same exercise with the GTC spectra, and the metallicities inferred from $N_2$ also agree: compare the $N_2$-based metallicity from the full galaxy GTC spectra, Table 2 column 4, with the metallicity worked out in Trujillo et al. (2017), Table 2 column 5. One final comment is in order. Note that the metallicity estimated for the diffuse component using HCm differs by 0.4 dex from the metallicity of the brightest star-forming knot (Table 2, column 1). In view of the error bars inferred from the Monte-Carlo simulation, we do not consider this difference to be significant, and our observation is consistent with UGC 2162 having a uniform metallicity.

$N/O$ in local galaxies increases with increasing gas-phase metallicity (e.g., Vincenzo et al. 2016) and can be used to constrain $O/H$. HCm also provides an estimate for $N/O$, which is consistent with $O/H$ if UGC 2162 follows the trend observed in local galaxies (e.g., Vincenzo et al. 2016). The first bright point turns out to have $\log(N/O) = -1.67 \pm 0.03$, or $-1.52 \pm 0.08$ if the Monte Carlo simulation is considered. These values correspond to $12 + \log(O/H) < 8.5$ (e.g., Figure 1 in Vincenzo et al. 2016), and so are compatible with the other determinations of the metallicity in UGC 2162.

\(^{13}\) We followed the step-by-step prescription described by Pérez-Montero (2017).
3. Results and Implications

Figure 4 shows the $M_e$ versus the gas-phase metallicity relation (MZR) derived for local dwarf galaxies by Berg et al. (2012; the red solid line, with the empty circles being the original data), as well as the relation inferred for all star-forming SDSS galaxies by Andrews & Martini (2013; the orange solid line and shaded region). Both rely on the DM to infer $12 + \log(O/H)$. The three blue squares represent three different estimates of the UGC 2162 metallicity as traced by the brightest knot, namely, the one inferred using HCm without O II emission lines, as it has been shown by, e.g., Calabrò et al. (2017). An inspection of Figure 5 shows that the surface SFR and the metallicity of UGC 2162 naturally fit the values inferred for the host galaxies. Moreover, its stellar and gas masses are also typical of an XMP galaxy (for reference, see Filho et al. 2013). Thus, UGC 2162 has the properties to be expected an XMP galaxy in a pre- or post-starburst phase, when the bright starburst has faded away and only the host galaxy remains. Its mere existence cleans up the difficulty posed by the lack of host-like galaxies without starburst (Section 1).

UGC 2162 is a galaxy with high gas-phase metallicity for its mass. It is not unique. Some of the emission-line galaxies at high redshift studied by Calabrò et al. (2017) also belong to this regime (Figure 4). In addition, Greco et al. (2018) have recently characterized two diffuse dwarf galaxies in the local universe similar to UGC 2162 in this respect, namely, LSBG-285 and LSBG-750. They are low stellar mass galaxies ($M_e \sim 2 - 3 \times 10^7 M_\odot$) with a gas-phase metallicity around half the solar value, which makes them high-metallicity outliers of the gas-phase MZR (the magenta squares in Figure 4). These two objects have their stellar metallicity ($Z_*$) estimated from the continuum emission. Although with large uncertainty, $Z_*$ is estimated to be low, between 3% and 10% of the solar metallicity. Thus, what is expected if the stars were produced during past starbursts feeding from metal-poor gas. Other works also show high-metallicity outliers of the MZR (e.g., Peeples et al. 2008, in the local universe, and Zahid et al. 2012, at redshift <0.4).

4. Discussion and Conclusions

Using spectra from the 10 m GTC telescope, we confirm the relatively high metallicity of the ionized gas forming stars in the UDG UGC 2162 (Section 2 and Table 2). This result...
together with its low stellar mass make UGC 2162 a high-metallicity outlier of the MZR (Figure 4). Its surface SFR is also low, so that UGC 2162 seems to have all the properties characterizing the host galaxies associated with the XMP galaxies (Sections 1 and 3). XMP galaxies have a low light-weighted mean metallicity \((Z < Z_\odot/10)\), which, however, is often not uniform. The metallicity is low only in the young off-center bright starburst that often gives XMP galaxies their characteristic tadpole morphology (see Section 1). However, the underlying galaxy hosting the starburst is significantly more metallic than the starburst. The properties of UGC 2162 make it a candidate to be one of such host galaxies (i.e., a headless tadpole galaxy).

Detecting galaxies with the properties of the hosts is essential for consistency, because they are expected if the lopsided starburst is created by external gas accretion. These hosts are galaxies left over after a major star formation phase, or they are precursors of XMP galaxies before a gas accretion event triggers new star formation episodes. We have found that UGC 2162 may be one of these. Moreover, there are also other galaxies populating the high-metallicity region of the mass–metallicity plane (see Section 3). These objects are usually underrepresented in emission-line galaxy surveys because they are faint, have low surface brightness, and have lines of low equivalent width. However, they may represent a fundamental phase in the star formation process of low-mass galaxies, which have a bursty SF history, with periods of high SF interleaved with others of inactivity.

Systematic searches for XMP galaxies based on galaxy spectra provide objects that usually comply with the definition of Blue Compact Dwarf (BCD) galaxies (e.g., Kunth & Östlin 2000; Morales-Luis et al. 2011; Sánchez Almeida et al. 2016). Thus, the XMPs mentioned in this paper, with luminous lopsided \(\text{H}\text{II}\) regions, seem to correspond to extreme cases of the more common BCDs. The same kind of duty cycle hypothetically linking XMPs and UDGs also fits in the relation between BCDs and their quiescent counterparts (QBHD). BCD galaxies are metal-poor systems for their stellar mass, presently going through a star-forming phase. Thus, they are relatively luminous with high surface brightness. Their outskirt light is
dominated by the host galaxy, so that star-forming regions and host can be separated out (e.g., Amorín et al. 2007). Using the properties of the host galaxies to search for QBCDs, one infers the existence of a population of QBCDs 30 times more numerous than the BCDs (Sánchez Almeida et al. 2008). As expected if BCDs and QBCDs alternate their roles cyclicly, $Z_{\star}$ is the same in both types of galaxies, and agrees with $Z_{\star}$ in BCDs, during the star-forming phase of the cycle (Sánchez Almeida et al. 2009). On the other hand, $Z_{\star}$ in QBCDs is significantly larger than that in BCDs (0.35 dex), as if their star-forming gas was already metal enriched. Their duty cycle also concurs with the luminosity-weighted ages of their respective stellar populations, being young in BCDs ($\lesssim$1 Gyr) and older in QBCDs (from 1 to 10 Gyr; Sánchez Almeida et al. 2009).

We hypothesize that the evolution of a single galaxy might be like this: from an initially quiescent state, with $Z_{\star} > Z_{\ast}$, as a result of a few Gyr of stellar evolution, and with $Z_{\star}$ equal to that in other quiescent galaxies of the same $M_{\star}$, an accretion event brings in relatively low-metallicity gas with $Z_{\text{in}} < Z_{\star}$, creating a local star formation spot with low metallicity compared to other regions in the galaxy. This would be the phase observed as BCD (or XMP) because of the increase in surface brightness and luminosity caused by star formation. $Z_{\text{in}}$ is comparable to $Z_{\ast}$ at the beginning of this phase, but soon after, star formation makes $Z_{\star}$ slightly larger than $Z_{\text{in}}$ and increases the stellar mass of the galaxy as well. When star formation stops, the galaxy turns quiescent again, increasing $Z_{\star}$ over the next few Gyr. As a result, $Z_{\star} > Z_{\ast}$ in the new quiescent phase, with the stellar metallicity being greater than it was before but still consistent with the mass–metallicity relation, as the stellar mass has also increased.

From the point of view of the cosmological simulations of galaxy formation, low-mass high-metallicity systems are to be expected (e.g., Lagos et al. 2016; De Rossi et al. 2017; Sánchez Almeida & Dalla Vecchia 2018). For fixed $M_{\star}$, the galaxies of high SFR have star-forming gas of low metallicity. When this gas is consumed through SF and outflows, the small fraction that remains to form stars is contaminated by metals injected during the past SF episodes, and thus, the leftover gas tends to be fairly metallic. At this point, the galaxy is under-luminous and of low surface brightness. Thus, galaxies like UGC 2162 would represent systems in the late stages of consuming the gas that led to the last major outburst. This scenario fits well with the formation processes for UDGs found in zoom-in cosmological simulations from the Numerical Investigation of a Hundred Astrophysical Objects (NIHAO) project (Di Cintio et al. 2017). Some of their objects are UDGs. They reside in isolated haloes, have $M_{\star}$ of $10^{7–8.5} M_{\odot}$, effective radii larger than 1 kpc, and dark-matter cores rather than cusps. They exhibit a broad range of colors, and a nonnegligible $M_{\star}$ of $10^{7–9} M_{\odot}$. The presence of gas turns out to be crucial to form UDGs. Gas needs to be accreted to trigger SF. Then, feedback-driven gas outflows, and the subsequent dark matter and stellar expansion, are the key to reproduce faint extended galaxies, in a process similar to the creation of dark-matter cores in dwarfs (e.g., Governato et al. 2010). Somehow, dwarf galaxies with particularly bursty and prolonged SF histories tend to be extended in size and, therefore, have low surface brightness when in between bursts. In their very recent paper, Chan et al. (2018) reach a similar conclusion, and they also predict the UDGs to have low $Z_{\ast}$.

The need of significant amounts of gas that cycle between the galaxy and its surrounding medium seems to be a central ingredient for the creation of very low surface brightness systems. UGC 2162 is a fairly gas-rich object, thus fitting well with this idea. However, for UGC 2162 to be truly consistent with the picture, its large gas reservoir cannot participate in the present residual SF. It has to be gas that either will fuel future SF once it settles down onto the disk, or gas driven out by past SF episodes. If the total mass of gas were participating in the SF, then according to the Kennicutt–Schmidt relation (K-S relation; e.g., Kennicutt & Evans 2012) the total SFR of the galaxy$^{15}$ would be around $6 \times 10^{-2} M_{\odot}$ yr$^{-1}$. The SFR of the main SF knot in UGC 2162 is around $8.7 \times 10^{-5} M_{\odot}$ yr$^{-1}$ (Trujillo et al. 2017), so that even if tens of knots like this one contribute to the total SF, they will never sum up to give the SFR expected if all the observed H I mass participates in the SF process.

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Software: Python, TOPCAT.

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15 Assuming $M_{\text{HI}} = 1.9 \times 10^{9} M_{\odot}$ and a H I radius three times the effective radius (i.e., 5.1 kpc; Trujillo et al. 2017), one gets a surface gas density of $3.3 M_{\odot} \text{ pc}^{-2}$. Then the K-S relation in Kennicutt & Evans (2012) gives a surface SFR of $6.9 \times 10^{-2} M_{\odot} \text{ yr}^{-1} \text{pc}^{-2}$, which integrated over the optical galaxy gives a SFR of $6.0 \times 10^{-2} M_{\odot} \text{ yr}^{-1}$. The Astrophysical Journal, 869:40 (7pp), 2018 December 10
