WITNESSING GAS MIXING IN THE METAL DISTRIBUTION OF THE HICKSON COMPACT GROUP HCG 31∗

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Received 2014 July 25; accepted 2014 December 4; published 2014 December 19

ABSTRACT

We present for the first time direct evidence that in a merger of disk galaxies, the pre-existing central metallicities will mix as a result of gas being transported in the merger interface region along the line that joins the two coalescing nuclei. This is shown using detailed two-dimensional kinematics as well as metallicity measurements for the nearby ongoing merger in the center of the compact group HCG 31. We focus on the emission line gas, which is extensive in the system. The two coalescing cores display similar oxygen abundances. While in between the two nuclei, the metallicity changes smoothly from one nucleus to the other indicating a mix of metals in this region, which is confirmed by the high-resolution Hα kinematics ($R = 45,900$). This nearby system is especially important because it involves the merging of two fairly low-mass and clumpy galaxies (LMC-like galaxies), making it an important system for comparison with high-redshift galaxies.

Key words: galaxies: evolution – galaxies: interactions – galaxies: kinematics and dynamics

1. INTRODUCTION

The most widely accepted scenario for the evolution of systems of merging galaxies predicts that large-scale gas flows are widespread and may already occur at first passage (e.g., Mihos & Hernquist 1996; Rupke et al. 2010a). Theoretical studies predict that in major mergers, tidal torques will develop bars and induce gas to lose angular momentum and flow toward the center, fueling massive central starbursts, active galactic nuclei (AGNs), and/or quasar activity (e.g., Barnes & Hernquist 1996). As shown by Torrey et al. (2012) and references therein, these inflows could either cause a depression in the nuclear metallicity of gas-poor disk–disk interactions (see Rupke et al. 2010b) or cause an enhancement in the central metallicity due to star formation in gas-rich disk–disk interactions, given that the metallicity of the merger remnant is mainly set by the competition between the inflow of low-metallicity gas and the enrichment from star formation. However, other factors such as gas consumption and galactic winds also contribute as secondary players (Torrey et al. 2012).

Although these large inflows in merging galaxies have been expected from simulations and theory, they have never been observationally witnessed mainly due to the lack of detailed kinematic data over a large extent of colliding systems and with sufficiently high spatial and spectral resolutions. In particular, in order to identify the various intertwined velocity components of the inflowing gas, one needs two-dimensional (2D) kinematic data over an extended area that is usually not delivered by Integral Field Units (IFUs) and with sufficiently high spectral resolution, typically $R > 30,000$. However, even if one had in hand high-resolution wide-field 2D velocity maps for a sample of mergers and close pairs, it would still generally be quite difficult to disentangle the individual gas kinematic components because signatures of AGN activity, shocked regions, and winds are often present, particularly in the case of strong inflows (Rich et al. 2011). AGN activity and shocks can blur the signatures of several components of the gas kinematics by broadening the lines, erasing gas peaks, and consequently mixing or altering the information.

According to the simulations of Mihos & Hernquist (1996), gaseous inflows are strongest when the colliding galaxies have dense central bulges and are in the final stages of merging, but these are especially strongly affected by shocks and AGN activity, which may cover up the kinematic inflow signatures and cause interpretation of the data difficult. Inflows in bulgeless galaxies, however, although expected to be weaker, tend to occur earlier in the interaction and are much less affected by shocks. Our best bet for directly witnessing gas flows in a colliding system is then to focus on the gas kinematic signatures of mergers of low-mass, late-type, disk–disk progenitors where bulges will be less important and AGN activity, shocks, and winds may play less of a role.

Here, we study an ideal group in which gas flows may be detected: the systems HCG 31A and HCG 31C in the compact group HCG 31, which are low-mass (both galaxies have masses similar to that of the Large Magellanic Cloud), low-metallicity (where member HCG 31C has a value of $12+\log(O/H) = 8.22$, López-Sánchez et al. 2004), and low-separation (projected separation of 3.5 arcsec or 0.9 kpc between the two merging nuclei). Amram et al. (2007) have found that the two merging nuclei are in a bound orbit with almost parallel spin axes, like a set of gear wheels, in a prograde encounter. The two merging cores have had at least one earlier passage and they have a high star-formation rate ($10.6 M_\odot$ yr$^{-1}$, Gallagher et al. 2010), being in an early stage of merger.

The main goal of this Letter is to show how the kinematics of the HCG 31AC system relates to its metallicity in the merger interface region along the line that joins the two merging nuclei. At the redshift of HCG 31 ($z = 0.013473$, NED database), 1″ = 0.26 kpc (for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). The Letter is

∗ Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência e Tecnologia (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina) – Observing run: GS-2012B-Q-60.
organized as follows. In Section 2, we describe the observations and data reduction. In Section 3, we present the results. Finally, a discussion and a summary of our results are presented in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Gemini/GMOS IFU Data

The central region of HCG 31 has been observed with the IFU (Allington-Smith et al. 2002) of the Gemini MultiObject Spectrograph (GMOS; Hook et al. 2004) at the Gemini South Observatory, under programme GS-2012B-Q-60. Three fields of view (see Figure 1) were observed using the R400 grating and the $r'$-band filter, and for each field we observed three exposures of 700 s with a mean seeing of 0.4″. The grating was centered at 6300 Å using the two slit mode, covering a spatial area of 5″×7″ for each field, from 5620 Å to 6960 Å. Data reduction was performed using the Gemini package in IRAF. The 2D images were transformed to a three-dimensional data cube and resampled as square pixels with 0.1″ spatial resolution and corrected by differential atmospheric refraction. The data was flux calibrated using the standard star LTT 4364.

Each spectrum of the data cube has been corrected for Galactic extinction using $E(B–V) = 0.04$ mag (NED database) and the Fitzpatrick (1999) extinction law. Internal extinction was corrected for using the Calzetti et al. (2000) extinction and an average nebular color excess of $E(B–V) = 0.08$ mag, which was estimated for the central region of HCG 31AC using the spectra published by Mendes de Oliveira et al. (2006). This approach was used because our IFU data do not include the Hβ emission line. Emission line fluxes were estimated with the interactive routine $\text{FLUXER}$ in IDL (code written by Christof Iserlohe).

2.2. Fabry-Perot Data

Observations were carried out in August 2000, at the ESO 3.6 m telescope in Chile, using the Fabry-Perot instrument CIGALE. A total of 48 channels were mapped with a free spectral range of 155 km s$^{-1}$, which produced a sample step of 3.2 km s$^{-1}$. The spectral resolution of this data set is $R = 45,900$ (see Amram et al. 2007). The pixel size is 0.405 arcsec pixel$^{-1}$ and the observations were taken with a mean seeing of 0.7 arcsec.

3. RESULTS

3.1. Determining the Oxygen Abundances

Given the spectral coverage of our observations, oxygen abundances were estimated using the strong line abundance indicator N2, which is defined as $N2 = \log ([\text{N}II] \lambda 6584/\text{H}\alpha \lambda 6563)$. We used the calibrator recently revised by Marino et al. (2013). We do not correct the spectra by Balmer absorption that may have been related to an underlying old population given the very weak continuum (López-Sánchez et al. 2004). We note that the empirical calibrations are based on oxygen abundances derived from the direct method and are affected by uncertainties related to the scatter on the calibration itself. Also, the use of different calibration methods on the same observational data set can produce differences in the estimated values. However, as pointed out by Bresolin et al. (2012), differential analyses are useful to minimize these discrepancies. In this analysis, uncertainties in the oxygen abundances were first estimated by propagating the flux uncertainties (derived from the task $\text{FLUXER}$) and considering the standard deviation in the zero-point and slope of the calibrator regression. Together, these typically amount to 0.03 mag. However, by far the largest source of error is the 0.16 dex scatter in the N2 calibration found by Marino et al. (2013). All of these uncertainties are added in quadrature. We also attempted to derive the metallicity gradient using the N2S2 prescription of Pérez-Montero (2014), but given the much lower fluxes of the used lines, the error bars are large. A third determination of the metallicity was employed using the GMOS data of HCG 31 published by Mendes de Oliveira et al. (2006). These authors obtained a spectrum through a slit placed across members HCG 31AC. These have been corrected for Galactic and internal extinction using the same extinction laws used for the IFU data and using the observed Hα/Hβ ratio for each extraction, with the corresponding intrinsic ratio taken from Osterbrock (1989) for $T_e = 10,000$ K and $N_e = 100$. The main nebular emission lines present in this latter data set are

![Figure 1. HST optical image (ACS, F435W) of the compact group HCG 31. The image shows the regions A+C, B, and part of the southeast tidal tail. The red squares show the three different regions where the IFU are located.](image-url)
Hβ, [O iii] 4959 Å, [O iii] 5007 Å, [N ii] 6548 Å, Hα, and [N ii] 6584 Å, and therefore oxygen abundances were estimated with the O3N2 indicator suggested by Marino et al. (2013).

In Figure 2, we show the oxygen abundance map of the central regions of HCG 31 (derived from the N2 calibrator) corresponding to the areas of the three red boxes of Figure 1. We find that the star-forming complex associated with HCG 31C has an oxygen abundance of 12+log(O/H) = 8.22 ± 0.17, while HCG 31A has an abundance of 12+log(O/H) = 8.44 ± 0.16. We note that the latter value was also measured along the bar-like structure that forms the eastern part of HCG 31A. The absolute numbers here are not important, given that they may change with calibrator.

Inspecting the central field of Figure 2, it can be noted that there is a smooth gradient between the two main starbursting complexes. Taking into account the uncertainties, the metallicities of these two complexes are similar, which suggests that the strong gravitational encounter between HCG 31A and HCG 31C is currently mixing their chemical content. This is in agreement with the general notion that strong interactions flatten metallicity gradients.

In order to emphasize this result, in Figure 3 we have plotted with filled circles the oxygen abundance gradient along the region that connects the strong star forming blobs of HCG 31C to those of HCG 31A, covering a very similar area (but smaller) to that shown by the seven green boxes in Figure 4 (see description of this figure in Section 3.2). This gradient was derived from the 2D abundance maps using the N2 method (in this case, we mimic a long slit observation). In Figure 3, we also show metallicity gradients using the other calibrators, O3N2 and N2S2 (filled triangles and empty stars, respectively). We see a smooth transition in the oxygen abundance gradient as measured by the N2 calibrator. The N2S2 calibrator shows the same trend; however, the scatter in this calibrator is large given the smaller signal-to-noise ratios (S/Ns) of the [S ii] lines (and for this reason we have binned these data in Figure 3). In the case of O3N2, the S/Ns are also poorer given that these come from a long-slit observation with few data points compared to the IFU determination of the N2 calibrator. Considering the uncertainties in the oxygen abundances, we find that the metallicities of HCG 31A and HCG 31C are compatible and the merger interface region displays a smooth gradient in the chemical abundance. Using a linear fit to the N2 measurements, we derived a gradient of 1.5×10^{-4} dex pc^{-1} for the oxygen abundances in HCG 31AC, which reflects that the metallicities of both systems are compatible. Given that we do not detect any discontinuity in the gradient, we can speculate that the smooth gradient is real. This indicates that gas mixing is taking place between these galaxies. This result is confirmed by kinematics, as we show in the following section.

3.2. Kinematics: Using High-resolution Fabry-Perot Data to Search for Gas Flows

Figure 4(a) shows the total flux (in arbitrary units) within the interference filter of the Fabry-Perot, around Hα (20 Å), roughly matching the Hubble Space Telescope (HST) image displayed in (d). The bar-like structure of HCG 31A (eastern part of the galaxy) can be readily seen here.

Figure 4(b) shows the velocity field of the same region, adapted from Amram et al. (2007). The velocity gradient in the region of interest (which corresponds to the location of panels 1–7 in panel (d) is essentially flat. In particular, the two main clumps of star formation (HCG 31C and A) display quite similar radial velocities. Indeed, the barycenter of the entire profile is used to compute the mean velocity displayed in the velocity field, and this quantity displays a small global shift. This is due to the fact that along the axis connecting the two coalescing regions, the relative intensity variation of each individual velocity component, pointed out in panels 1–7, roughly compensates the velocity shift during the computation of the barycentric radial velocity. The velocity gradient is thus smooth and without evidence of a kinematical feature due to different velocities in the two main blobs. Nevertheless, as will be described below, there is a clear shift in velocity seen for each individual velocity component that forms the Hα profile which cannot be seen in the global radial velocity pattern of the system.

Figure 4(c) shows the velocity dispersion map, adapted from Figure 8 of Amram et al. (2007). The dispersion is very high in
Figure 3. Oxygen abundance gradient extracted from the map shown in Figure 2. This gradient was derived by simulating a long slit passing through the seven green boxes displayed in Figure 4. Black filled circles, black filled triangles, and empty stars represent the oxygen abundances derived from the N2, O3N2, and N2S2 methods, respectively. This gradient was estimated along the two main star forming nuclei of HCG 31C and HCG 31A, respectively. In the case of the N2 gradient, the sampling was chosen to match the seeing, and in the case of the N2S2 calibrator we have binned the data given the low S/N of the [S ii] lines.

Figure 4. (a) Total flux (in arbitrary units) within the interference filter of the Fabry-Perot, around Hα (20 Å), roughly matching the HST image displayed in (d), shown in logarithm scale. (b) and (c), adapted from Amram et al. (2007), are the velocity field and velocity dispersion maps corresponding to the same field shown in (a). Note that the contours of panel (a) are overplotted in (b) and (c) for clarity. (d) Optical HST image of HCG 31—a zoom from the larger region shown in (e). The green boxes on (d) correspond to the vertical panels on the left, labeled 1–7, which indicate the regions for which we have extracted the Hα profiles (from the Fabry-Perot data). These profiles are normalized to the size of the box. Note that in black we show the integrated profile and in color we highlight the components for which we can follow the velocity shift (left to right) from top to bottom (north to south).

the merger-interface region (red and pink regions in the map). The contrast between the high- and low-dispersion regions is even more obvious when looking at the large-scale figure given in Figure 8 of Amram et al. (2007), which also shows that some other high-dispersion regions exist. The high values in the velocity dispersion map can be explained by the broadening of the Hα profiles due to the presence of the several components as those displayed in panels 1–7. Outside this region, the velocity dispersion values are lower (from blue to yellow, in the map). We do not see any spatial coincidence between the high-velocity dispersion region in panel 4c and the regions of highest intensity in panel 4a, suggesting that the broadening of the profiles is not
only linked with star formation, otherwise we would expect a
direct correlation. We then speculate that there is room for the
presence of a flow that carries the gas.

We have used the package PAN6 in IDL to fit multiple
Gaussians to the observed Fabry-Perot Hα profiles of the central
regions of HCG 31AC. Given the high spectral resolution of the
Fabry-Perot observations and the complexity of the system, it is
not possible to have a unique solution for the multiple Gaussian
fitting process. In the fit we performed, we attempted to use
the smallest number of Gaussians, which resulted in five main
components that came out naturally from the best-fit profile de-
composition. Center, width, and intensity were free parameters.

In panels (d) and (e) of Figure 4, we show an archival ACS HST image of HCG 31 (filter F435W). In (d), the green squares (0'.8×0'.8 or 208×208 pc each) represent the regions for which we have extracted Hα profiles (these are shown as black continuum lines in panels 1–7). With color Gaussians of different intensities, we show the several velocity components. We claim that these are moving from left to right as we inspect the panels from top to bottom (north to south). In the following, we demonstrate our claim using two components, green and red. Both components can be readily seen in panel 1 with central velocities 3957 km s−1 and 3978 km s−1, respectively. In panel 2, we see the green component decrease its intensity by about 50% and the red component increase its intensity by ∼10%–20%, and they shift by 4 km s−1 and 15 km s−1 to the right, respectively. In panel 3, the red component remains at the same radial velocity and the green component is shifted by 6 km s−1 to the right, but with lower intensity. The scenario is different for panel 4. Inspecting the optical HST image at this location, we can see a region of lower flux in between the two clumps. Nevertheless, the Hα profile is high—it has similar intensities to panels 1 and 2. In panel 4, the green and red components are shifted to the right by ∼15 km s−1 and ∼7 km s−1, respectively, and the intensity of both components decrease compared to panel 3. In panel 5, the intensity of the green component increases but its velocity remains unchanged. The red component has its intensity increased by about a factor of two and moves ∼11 km s−1 to the right. The green component is again not shifted in panel 6 and the red component moves ∼2 km s−1. In panel 7, the green and red components move to the right by ∼10 km s−1 and ∼4 km s−1, respectively. Thus, from panels 1 to 7, the green and red components move a total of ∼33 km s−1 and ∼37 km s−1, respectively. All of the above descriptions suggest that an ionized gas component is moving along the ridge that traces the merger interface between A and C. In general, all of the components show a regular shift to higher velocities, from north to south.

In conclusion, the gas flow that we detect is widespread, traced by the high-velocity dispersion regions of the map, and, in particular, is present in the merger interface region along the line that joins the two coalescing nuclei.

4. DISCUSSION AND SUMMARY

In this Letter, we report for the first time direct observational
evidence of metal mixing in merging galaxies. We detect a smooth metallicity distribution between two strong bursts
of star formation associated with two different interacting
galaxies, namely, HCG 31A and HCG 31C. The analysis of
high-resolution Hα Fabry-Perot data reveals the presence of
multiple Hα emission line components in the merger interface
along the line that joins HCG 31A to HCG 31C main star
forming complexes. A systematic shift in the radial velocity
of these components supports the idea of gas flows. This
gas flow should be the main factor responsible for producing
a smooth metallicity connection between these objects. This
observational result is in agreement with recent results obtained
in simulations, i.e., interactions and mergers induce gas inflows
toward the center of the galaxy, diluting the central abundances
and producing flat metallicity gradients (Rupke et al. 2010a;
Perez et al. 2011). In addition, strong bursts of star formation
are triggered, as found in recent simulations (Hopkins et al.
2013). We are witnessing this process in an early stage merger
where the main burst associated with each galaxy still retains
its original metallicity, but a smooth and fairly flat gradient
connects both systems.

We warmly thank Thierry Contini, Marianne Girard, Enrique
Pérez-Montero, Carolina Kehrig, Angel López-Sánchez, and
Raffaela Marino for insightful discussions that improved this
manuscript and Enrique Pérez-Montero for making his code
HI-CHI-MISTRy available to the community. Based on observations
made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science
Institute. STScI is operated by the Association of Universities
for Research in Astronomy, Inc. under NASA contract
NAS 5-26555. S.T.-F. acknowledges the financial support of
FONDECYT through a project “Iniciación en la Investigación,”
under contract 11121505 and the support of the project CONI-
CYT PAI/ACADEMIA 7912010004, C.M.dO. and P.A. thank the
support of USP/COFECUB. C.M.dO. acknowledges support
from FAPESP and CNPq. M.A.C. acknowledges the financial
support of the Dirección de Investigación of the Universi-
dad de La Serena, through a “Concurso de Apoyo a Tesis 2013”
number PT13146.

Facilities: Gemini:South (GMOS), ESO:3.6m (CIGALE)

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