

# Resolved properties of a luminous hinge clump in the compact group of galaxies NGC 6845

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## ABSTRACT

**Context.** Compact groups of galaxies are unique places where galaxy-galaxy interactions play a mayor role on the evolution of its members. These strong gravitational encounters can induce star formation bursts.

**Aims.** We study the properties of one of the most luminous so-called hinge clumps that is located in the compact group of galaxies NGC 6845.

**Methods.** Using integral field spectroscopy from GMOS/Gemini complemented with archival MUSE data, we obtained oxygen abundances, ages, star formation rates, and velocity fields, and we also modeled a single stellar population to understand the star formation history of the hinge clump in NGC 6845.

**Results.** We found that the hinge clump sits in a tail that has a star formation rate of  $3.4 M_{\odot} \text{ yr}^{-1}$ , which is comparable with a few other extreme cases, for instance, the star clusters in the Antennae galaxy and other reported hinge clumps in the literature. This clump represents  $\sim 15\%$  of total star formation rate of NGC 6845A. Large-scale modeling of the observed velocity field of NGC 6845A rules out the scenario according to which this hinge clump was a satellite galaxy. Its kinematics is compatible with that of the galactic disk of NGC 6845A. Its abundance with a mean value of  $0.4 Z_{\odot}$  is also consistent with the metallicity gradient of the galaxy.

**Conclusions.** Our analysis suggest that the hinge clump is formed by multiple stellar populations and not by a single burst. This causes the wide age range. We found that the central clump is encompassed by a ring-like structure, which might suggest a second generation of star formation. In addition, the analysis of the diagnostic diagram indicates that this central region might also be ionized by shocks from stellar and supernova winds. Finally, the derived star formation rate density  $\Sigma = 9.7 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  of the central clump places it in starburst regime, where gas inflows should provide gas to maintain the star formation. This work shows a resolved example of an extreme localized starburst in a compact group of galaxies.

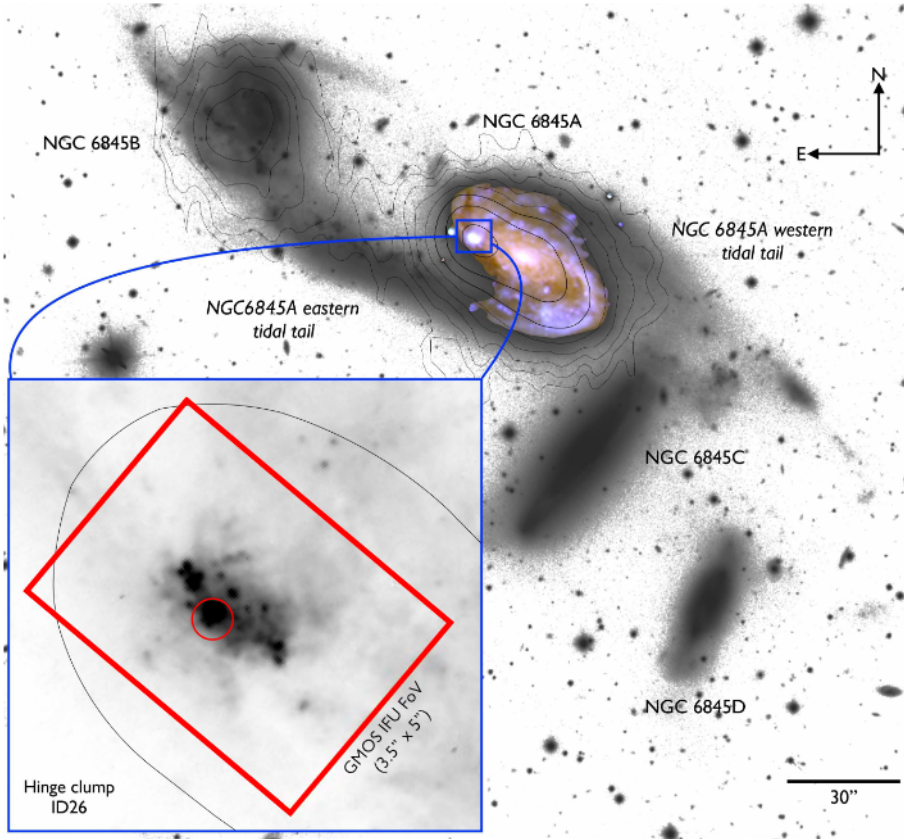
**Key words.** ISM: abundances – HII regions – galaxies: interactions – galaxies: ISM – galaxies: star clusters: general

## 1. Introduction

It is well known that interacting galaxies provide an extraordinary place for studying galaxy transformation and evolution. Here, different physical phenomena occur when galaxies interact. For instance, interactions can produce violent central starbursts that significantly enhance the integrated star formation in galaxies (e.g., Bekki et al. 2002; Renaud et al. 2016; Shah et al. 2022). An important fraction of this enhanced star formation can be linked to the formation of massive compact star clusters (e.g., Whitmore et al. 2010; Linden et al. 2021; He et al. 2022). These interactions also produce tidal tails, in which low-level star formation can be detected (e.g., Knierman et al. 2003; Mullan et al. 2011). This shows that interacting galaxies provide a natural place for studying star formation at different levels.

In tidal tails of interacting galaxies, different authors have found from tidal dwarf galaxies (TDGs; e.g., Duc & Mirabel 1998; Mendes de Oliveira et al. 2006; Bournaud et al. 2007) to low-mass star-forming regions and stellar clusters (e.g., Li et al.

2004; Tranco et al. 2007; Bournaud et al. 2008). Most of these systems display quite low star formation rates. TDGs are typically formed at the tip of tidal tails. Some authors argued that these systems do not contribute significantly to the population of dwarf galaxies (e.g., Ploetckinger et al. 2017), while other authors suggested that these systems will fade out in some billion years (e.g., Román et al. 2021). However, at the base of tidal tails, the scenario is quite different. Hancock et al. (2009) reported two luminous star-forming regions at the base of the northern and southern tidal tails of NGC 4017. They called these sources hinge clumps. The  $H\alpha$  luminosities of these clumps exceed  $10^{40} \text{ erg s}^{-1}$ . Therefore, these sources appear to be extranuclear starburst regions. More recently, (Smith et al. 2014) used multiwavelength imaging data to study the physical properties of a sample of 12 hinge clumps that are located in five interacting systems. The authors found star formation rates as high as  $9 M_{\odot} \text{ yr}^{-1}$ . This high-level star formation can be explained by converging gas flows in well-defined pile-up zones. The convergence is induced by orbit crowding, as shown by the



**Fig. 1.** Gemini/GMOS  $r'$ -band high-contrast image of the compact group of galaxies NGC 6845. The central region of NGC 6845A is overplotted with an  $u'$ ,  $g'$ , and  $r'$ -band composite image. The extranuclear star-forming region (hinge clump ID26) is identified in a blue box. Optical HST archival imaging ( $F606W$ ) highlights the central structure of this star-forming complex (zoomed blue box), where we overplot the Gemini/GMOS IFU field of view. The black contours represent the 20 cm continuum taken from [Gordon et al. \(2003\)](#). The red circle in the zoomed box corresponds to the peak of the continuum  $H\alpha$  emission (see Fig. 3).

analytic models developed by [Struck & Smith \(2012\)](#). The central optical sources of hinge clumps can reach 70 pc, and the stellar populations of the clumps span a different range of ages and are not just one single stellar population ([Smith et al. 2014](#)). The fate of hinge clumps is unclear, and it might depend on the properties of each interacting system. Therefore, a detailed analysis of these star-forming source systems is relevant for understanding its physical and kinematical properties. These reasons motivated us to perform an in-depth spectroscopic study of the brightest star-forming region located in the compact group of galaxies NGC 6845 using integral field spectroscopy and archival imaging data. The  $H\alpha$  luminosity of this region is comparable with star-forming sources located in the Antennae merging system. The region is comparable to the most luminous sources in the sample of 700 star-forming complexes belonging to interacting galaxies, as studied by [Smith et al. \(2016\)](#), which means that this object is a very interesting system that can help us understand the resolved properties of hinge clumps in more detail.

The compact group of galaxies NGC 6845 was studied by [Klemola \(1969\)](#), [Graham & Rubin \(1973\)](#), [Rose & Graham \(1979\)](#), [Rodrigues et al. \(1999\)](#), [Gordon et al. \(2003\)](#), [Olave-Rojas et al. \(2015\)](#), [Gimeno et al. \(2021\)](#). It is composed of four interacting galaxies labeled A, B, C, and D (as shown in Fig. 1). The main galaxy of this group is NGC 6845A, which displays the most prominent and extended tidal tail of the system. At the outskirts of its disk, indicated in the blue box in Fig. 1, lies an extremely bright source that is located at the base of the northern tidal tail. This source is the brightest of all H II regions visible in the disk and tidal tails of this group. It was first reported by [Graham & Rubin \(1973; knot a in their work\)](#), who described it as “one exceptional and large knot”. The spectroscopic observations developed by these authors revealed strong emission

lines. Using spectroscopic information, [Rose & Graham \(1979\)](#) later determined its heliocentric velocity, measuring a value of  $v_h = 6170 \pm 40 \text{ km s}^{-1}$ . [Rodrigues et al. \(1999\)](#) found that this region (object 7 in their work) is young ( $\sim 5 \text{ Myr}$ ) and bright ( $\sim 10^{40} \text{ erg s}^{-1}$ ). In addition, these authors suggested that this source is associated with a star-forming complex at the end of a bar in NGC 6845 A. [Gordon et al. \(2003\)](#) studied the H I<sup>1</sup> distribution in this system, finding that the 20 cm continuum peaks at the position of this bright star-forming region. [Olave-Rojas et al. \(2015\)](#) used Gemini/GMOS imaging and spectroscopic data to derive the physical properties of the H II regions in NGC 6845<sup>2</sup>, where the brightest star-forming region was called 26. These authors found that this source is ionized by star formation and has a quite high extinction and an oxygen abundance of  $12 + \log(\text{O}/\text{H}) \sim 8.45$ . Hereafter, the extranuclear star-forming region we analyzed is called ID26, following [Olave-Rojas et al. \(2015\)](#). More recently, [Gimeno et al. \(2021\)](#) studied the compact group NGC 6845 and focused on the lenticular galaxies NGC 6845C and NGC 6845D.

The paper is structured as follows. In Sect. 2, we present the data. In Sect. 3, we present the physical properties of ID26. In Sect. 4, we present the kinematic analysis of region ID26 from a local and global point of view. In Sect. 5, we discuss the possible scenarios that might explain the formation of this region. Finally, in Sect. 6, we present our main conclusions. Through-

<sup>1</sup> H I observations were made by using the Australia Telescope Compact Array (ATCA), during 1997 and 1998 (see [Gordon et al. 2003](#)).

<sup>2</sup> Images and spectra for NGC 6845 used in [Olave-Rojas et al. \(2015\)](#) were taken with the Gemini Multi-Object Spectrograph (GMOS; [Hook et al. 2004](#)) at the Gemini South telescope under the science program GS-2011B-Q-36 (PI: S. Torres-Flores).

out this paper, the adopted distance to NGC 6845 is 91.79 Mpc (Fixsen et al. 1996).

## 2. Data

### 2.1. Archival optical imaging data: Gemini and the Hubble Space Telescope

Optical imaging ( $u'$ ,  $g'$ , and  $r'$ -band) of the group NGC 6845 was obtained at the Gemini South Observatory using the Gemini Multi Object Spectrograph (GMOS, Hook et al. 2004) on September 24, 2011, and on September 16 and 18, 2012 (Program ID: GS-2011B-Q-36; PI: S. Torres-Flores). The details of the data reduction can be found in Olave-Rojas et al. (2015). In addition, we used archival data of the *Hubble* Space Telescope (HST) Advanced Camera for Surveys (ACS; Program ID:15446; PI: J. Dalcanton). The HST imaging of NGC 6845 was obtained with filter  $F606W$ , allowing us to disentangle the different clumps that belong to region ID26. Figure 1 shows a high-contrast  $r'$ -band image of the system. For the central region of NGC 6845A, we show a false-color image of the system based on the  $u'$ ,  $g'$ , and  $r'$ -band filters (blue, green, and red, respectively). The black contours represent the 20 cm continuum emission (taken from Gordon et al. 2003). In the inset we include a zoom into region ID26, where we show its resolved morphology based on the HST image. A central knot can be identified. The red rectangle represents the field of view (FoV) of the Gemini/IFU observation.

### 2.2. Spectroscopic data

#### 2.2.1. Slit data

Olave-Rojas et al. (2015) published the spectroscopic data of 28 star-forming regions located in the group NGC 6845, in which region ID26 was included as well. These observations were taken with the GMOS instrument on Gemini South (Program ID: GS-2011B-Q-36; PI: S. Torres-Flores), and the details of these observations can be found in Olave-Rojas et al. (2015). In addition, region ID26 was observed with the Echelle double spectrograph *Magellan* Inamori Kyocera Echelle (MIKE; Bernstein et al. 2003) at the 6.5 m *Magellan* II (Clay) Telescope on Las Campanas Observatory during the night of September 26, 2014 (PI: S. Torres-Flores). These observations were taken under a seeing of  $\sim 0.7$  arcsec, using an effective slit width of 1 arcsec. Flux calibration was performed by observing the standard star Feige 110 (Bohlin et al. 2001) under the same observing conditions. In this paper, MIKE observations are mainly used to compare the different flux calibrations obtained with Gemini (see Sect. 2.2.2) and MUSE data (see Sect. 2.2.3). MIKE observations of region ID26 and other extranuclear star-forming regions located in interacting systems will be discussed in a dedicated paper (Firpo et al., in prep.).

#### 2.2.2. Gemini GMOS integral field spectroscopy

The compactness of region ID26 means that integral field spectroscopy (IFS) is in the ideal method for studying the physical properties of this source. IFS observations were obtained at the Gemini South telescope using the GMOS Integral Field Unit (IFU; Allington-Smith et al. 2002) in the one-slit mode configuration (program ID: GS-2016A-Q-46; PI: S. Torres-Flores), which has an FoV of  $3.5'' \times 5''$  with a pixel scale of  $0.1''$ , equivalent to a scale physics of 44.5 pc according to the adopted dis-

tance of NGC 6845. In order to cover the main nebular emission lines associated with this object (e.g., H $\beta$ , [OIII], [NII], H $\alpha$ , and [SII]), we used the gratings R831 and B1200. For grating R831, we obtained three exposures of 1170 seconds each, centered at 6550 Å, 6600 Å and 6650 Å, under mean seeing conditions of 0.7 arcsec. For grating B1200, we obtained three exposures of 1170 seconds, centered at 4400 Å, 4450 Å, and 4500 Å, under a mean seeing of 0.56 arcsec. Flats and arcs were taken right after each science exposure in order to minimize possible flexures that might affect the precision of our measurements. The IFU/GMOS data were reduced using the standard IRAF<sup>3</sup> Gemini data reduction package. Cosmic rays were corrected for using the Python version of the LA COSMIC routine from van Dokkum (2001). Finally, the sensitive curve of the spectra was obtained using the standard star LTT 7987. Instrumental widths were measured by fitting a Gaussian profile on the arc lines. We estimated full width at half maximum (FWHM) values of 0.7 Å and 1.5 Å for B1200 and R834, respectively.

We used MIKE observations for a flux calibration of the IFU GMOS observations. In order to perform a correct alignment between the MIKE and GMOS observations, we first took the  $r'$ -band image from GMOS (Olave-Rojas et al. 2015) as a reference. Both observations were centered at the peak of region ID26. In a second step, we integrated the H $\alpha$  and H $\beta$  fluxes from GMOS data within an aperture of  $1''$  to mimic the integrated echelle fluxes from the MIKE observation. Finally, based on the ratio of these observations, we obtained the respective calibration factors.

#### 2.2.3. Archival complementary MUSE data

In order to have a global view of the system and to clarify the origin of region ID26, we used archival data observed with the Multi Unit Spectroscopic Explorer (MUSE; Henault et al. 2003; Bacon et al. 2004, 2010) at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). Observations of NGC 6845 were obtained in the wide-field mode (Program ID 0103.A-0637(A); PI: B. Husemann), reaching an FoV of  $3.34$  arcmin<sup>2</sup>, covering NGC 6845 A and NGC 6845 B. The data were acquired under a mean seeing of 1.8 arcsec, with a total exposure time of 2640 s, covering from 4750 to 9350 Å. We note that the individual analyses of region ID26 were performed by using the GMOS IFU data mainly because the spatial resolution is higher.

## 3. Physical properties

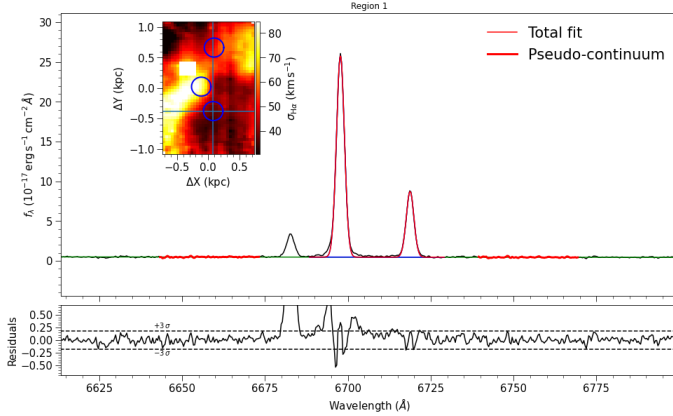
### 3.1. Emission line maps

The emission line maps were computed by using PYTHON package ASTROCUBELIB<sup>4</sup> (Hernandez-Jimenez 2024a). The line fluxes were calculated by integrating the area of the line profiles within a range of 10 Å around the Gaussian peak of the line. The program also provides the Gaussian centroid, equivalent width, and Gaussian  $\sigma$  of each emission line. Continuum maps were computed by integrating spectral windows of 30 Å at a distance of 20 Å from the Gaussian centroid of the line. However, in the

<sup>3</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operate/d by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. See <http://iraf.noao.edu>

<sup>4</sup> <https://gitlab.com/joseaher/astrocubelib>





**Fig. 2.** Example of an  $H\alpha$  line profile for the central spaxel of region 1. The main panel shows the observed spectrum (black lines) within the  $H\alpha$  window. The red line shows the fitted Gaussian profiles for the  $H\alpha$  and  $[NII] \lambda 6583$  lines, and the bold red intervals are the continuum windows we used to fit the continuum. The bottom panel shows the residual of the fit. The inset shows the  $\sigma_{H\alpha}$  map (in a large scale in the top right panel of Fig. 8). The blue cursor indicates the single spaxel where the spectrum was taken. The blue circles label the regions we analyzed (see details in the text).

case of  $H\alpha$  and  $[NII] \lambda 6583$ , which were fit simultaneously, the blueshifted spectral windows were at a distance of  $25 \text{ \AA}$  from  $H\alpha$  Gaussian centroid to avoid contamination of the continuum for the  $[NII] \lambda 6548$  line. The continuum contribution in the emission lines was then computed by fitting a linear function on the continuum windows.

In Fig. 2 we show an example of the fitting process in the case of the  $H\alpha$  and  $[NII] \lambda 6583$  emission lines. We note that due to the redshift of the galaxy, the  $[SII] \lambda 6731$  line falls into a sky band and is then strongly absorbed. Therefore, we did not obtain electron densities for region ID26.

Figure 3 shows the HST image (top left), the  $H\alpha$  map (top middle), the continuum map (top right), the  $[OIII]$  map (bottom left), and the  $[NII]$  and  $[SII]$  maps (bottom middle and bottom right, respectively). The  $H\alpha$  map shows a strong peak in the southern direction (hereafter called Reg. 1) and a secondary knot in the northeast direction (hereafter called Reg. 2), which are represented by black circles with a diameter of  $0.7 \text{ arcsec}$  in Fig. 3 (consistent with the seeing). The  $[NII] \lambda 6583$  and  $[SII] \lambda 6731$  emission line maps present a similar morphology. The  $H\alpha$  continuum map shows a strong peak at the center of region ID26 (hereafter called Reg. 3), in agreement with the high-resolution image of the HST (see Fig. 1). It is worth noting that this central clump in reality consists of many knots, as seen in the HST image. On the other hand, the  $[OIII]$  map displays two peaks at the center and in the western direction. This morphology resembles the structure of star-forming complexes located in interacting systems such as HCG 31 (Alfaro-Cuello et al. 2015), where the feedback of the continuum source appears to trigger star formation. The left panel of Fig. 3 shows the HST image for a clear overview of the spatial structure within region ID26. However, it is important to note that it can be challenging to directly compare this image with the GMOS observations because the spatial resolution in the two images is different. Nonetheless, when we degrade the HST image, its morphological distribution becomes comparable to that of the continuum map obtained from the GMOS observations. The study regions are overlaid onto the HST image for reference.

### 3.2. Gas extinction

In order to correct the  $H\alpha$  fluxes for extinction, we followed the same procedure as in Oliveira et al. (2022). We first applied a Voronoi binning on the  $H\beta$  image (Cappellari & Copin 2003). Our objective was to achieve a target signal-to-noise ratio (S/N) of 10 per tessellation bin. Subsequently, we generated an analogous tessellation map on the  $H\alpha$  image. For the theoretical  $H\alpha/H\beta$  ratio, we assumed a value of 2.86, which corresponds to the recombination case B for an electronic temperature of  $10000 \text{ K}$  (Osterbrock 1989), and we used the extinction curve published by Cardelli et al. (1989).

Figure 4 displays the results of the extinction correction process. As a reference, the top left panel shows the  $H\beta$  map. The top right panel shows the  $H\beta$  map after Voronoi tessellation was applied. The bottom left panel shows the extinction map,  $A_v$ , in magnitude. The bottom right panel displays the  $H\alpha$  map corrected for internal extinction. A comparison between the extinction map and the inset shown in Fig. 1 demonstrates the recovery of the dust lane passing through region ID26. The extinction in this particular region is around  $3 A_v$  magnitudes. A comparison between the observed  $H\alpha$  map (left panel in Fig. 3) and the extinction-corrected  $H\alpha$  map also shows that the most luminous clump of region ID26 is obscured by the dust lane.

### 3.3. Oxygen abundances

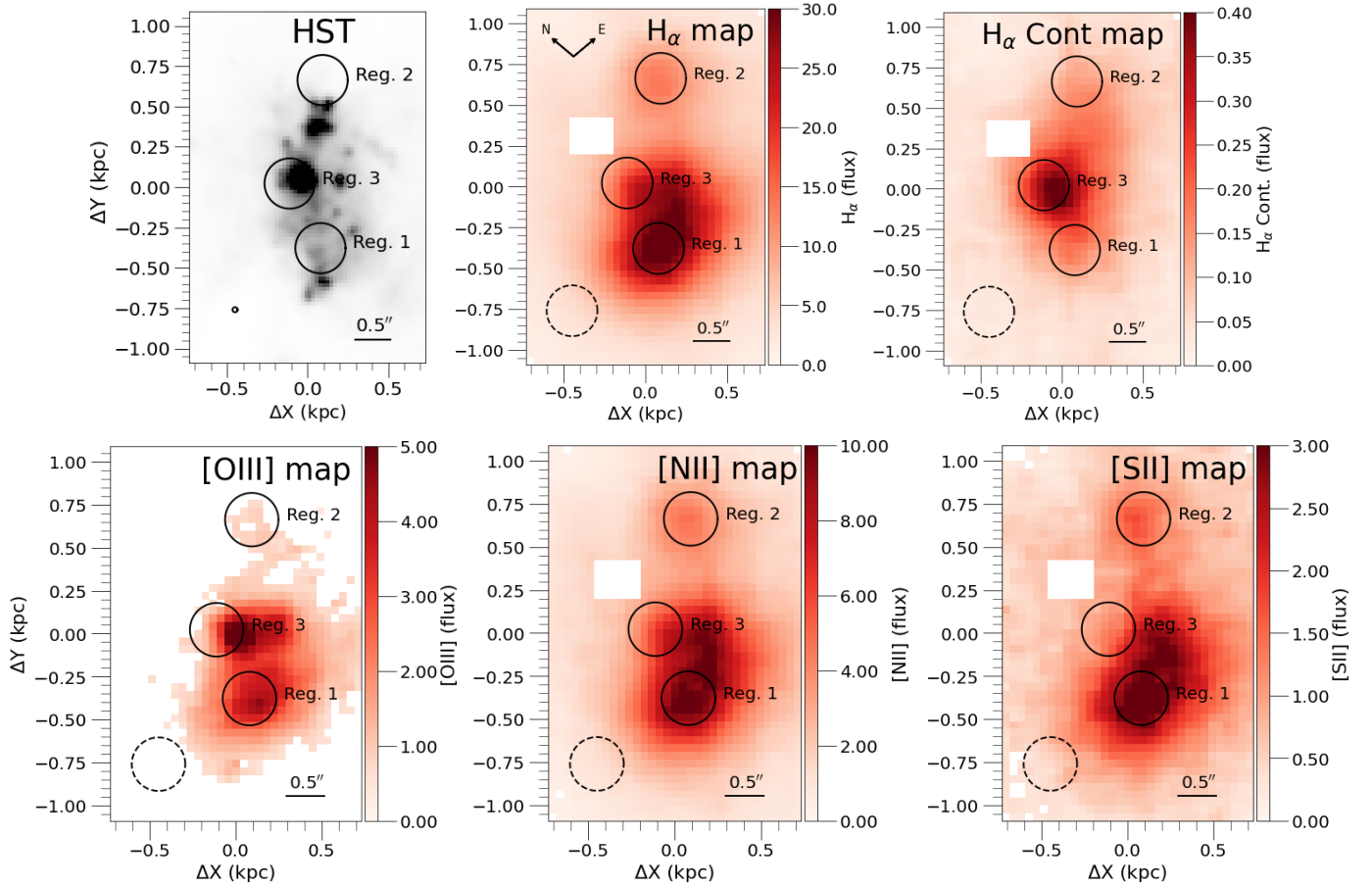
Using the emission line maps described above, we derived oxygen abundance maps by using the N2 (Storchi-Bergmann et al. 1994) and O3N2 (Alloin et al. 1979) indexes and the calibrations proposed by Marino et al. (2013), which were estimated using integral field observations from the Calar Alto Legacy Integral Field Area survey (CALIFA; Sánchez et al. 2012). Marino et al. (2013) reported a dispersion of 0.18 and 0.16 dex in their calibration for O3N2 and N2, respectively. We did not adopt the direct method because we did not cover the  $[OII]$  auroral line. In Fig. 5 we show the oxygen abundance maps for region ID26, based on the N2 and O3N2 indexes (left and right panels, respectively). The maps show low degrees of variation, between the 16th and 84th percentiles across the field of view, of  $12 + \log(O/H)_{N2} = 8.52^{+0.01}_{-0.01}$  and  $12 + \log(O/H)_{O3N2} = 8.52^{+0.02}_{-0.03}$ , and both maps have the same mean value of the metallicity. Assuming a solar metallicity ( $Z_\odot$ ) of  $12 + \log(O/H)_\odot = 8.89$  (Anders & Grevesse 1989), the mean value in region ID26 is  $0.4 Z_\odot$  (based on the O3N2 calibrator). Our values are consistent within  $1\sigma$  with those previously estimated by Olave-Rojas et al. (2015) for this source.

We did not find significant differences for the N2 index:  $12 + \log(O/H)_{N2}$  of  $8.51 \pm 0.01$ ,  $8.52 \pm 0.01$ ,  $8.51 \pm 0.01$  for Reg. 1, Reg. 2, and Reg. 3, respectively. In this case, we considered the dispersion on the measurements inside each region as the uncertainty. On the other hand, for the O3N2 index, the abundance derived for region Reg. 3 ( $12 + \log(O/H)_{O3N2} = 8.43 \pm 0.03$ ) is 0.1 dex lower than the values determined for Regs. 1 and 2 ( $12 + \log(O/H)_{O3N2} = 8.52 \pm 0.1$  and  $8.56 \pm 0.1$ , respectively).

In the large-scale context, the mean value of the metallicity of region ID26 seems to follow the metallicity gradient of NGC 6845 (Olave-Rojas et al. 2015), which suggests that the gas that triggers the star formation belongs to the disk of NGC 6845A.

### 3.4. Ionization mechanism

An ionization mechanism diagnostic diagram (hereafter BPT; Baldwin et al. 1981) is shown in the left panel of Fig. 6. The



**Fig. 3.** Flux maps of region ID26. The top panels from left to right show the HST  $H\alpha$  map and the integrated continuum flux around the  $H\alpha$  line maps. The bottom panels show from left to right the  $[OIII]\lambda 5007$ ,  $[NII]\lambda 6583$ , and  $[SII]\lambda 6731$  maps. The flux maps are in  $\times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1} \text{ pixel}^{-1}$  units. The intensities in the maps are shown in different ranges to highlight the substructures in region ID26. The dashed circle in the bottom right corner represents the seeing. The horizontal bar represents the angular scale. All IFU/GMOS panels show a white square that corresponds to poor fibers in the IFU/GMOS.

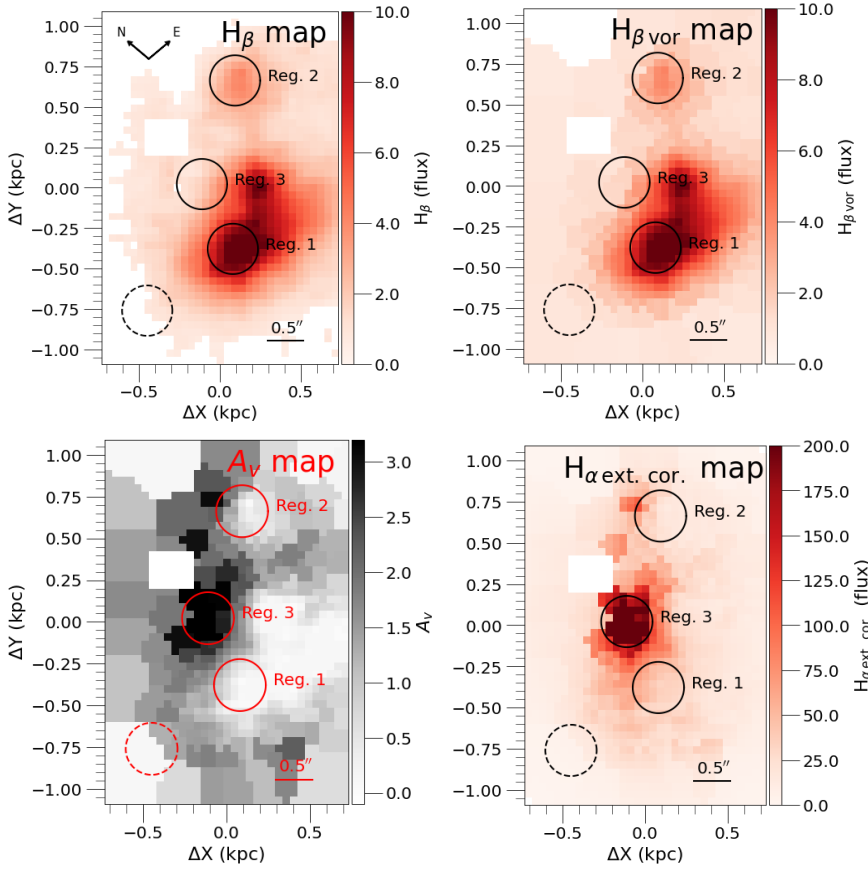
BPT diagram is color-coded following the  $EW_{H\alpha}$  map, which is shown in the right panel of Fig. 6. The BPT diagram shows photoionizing (black grids) and shock-ionizing (gray grids) models overplotted in order to explore the dominant ionization mechanism of region ID26. These plots were made using the PYTHON package ASTROISMLIB<sup>5</sup> (Hernandez-Jimenez 2024b). In addition of the individual spaxels, we also display the integrated information for Reg. 1, 2, and 3 (shown by a square, triangle, and diamond, respectively). The photoionizing and shock-ionizing models were taken from Kewley et al. (2001) and Allen et al. (2008), respectively. Both models were computed using the gas-ionization code MAPPING III (Sutherland & Dopita 1993; Sutherland et al. 2013). Most of the spaxels within the observed region are ionized by star formation. This trend is noticeable across a wide range of ionization parameters ( $q$ ), falling within the interval of  $q = [5 \times 10^6, 4 \times 10^7] \text{ cm s}^{-1}$ . In addition, there is a discernible positive gradient in the ionization parameter toward the center of ID26 (Reg. 3), which suggests a high level of star-forming activity in that area. However, it is worth noting that the central region of ID26 also intersects with the model associated with low-velocity shocks ( $200\text{--}300 \text{ km s}^{-1}$ ). This suggests the possibility that a dual mechanism, photoionization and shock-ionization, acts simultaneously in this region. The sources of these shocks may include a combination of supernovae and pow-

erful stellar winds. As discussed in Sect. 4.1, the  $H\alpha$  line profiles throughout region ID26 exhibit signatures of multiple kinematic components, strongly indicating a complex kinematic behavior that may be due to the presence of stellar and supernova winds.

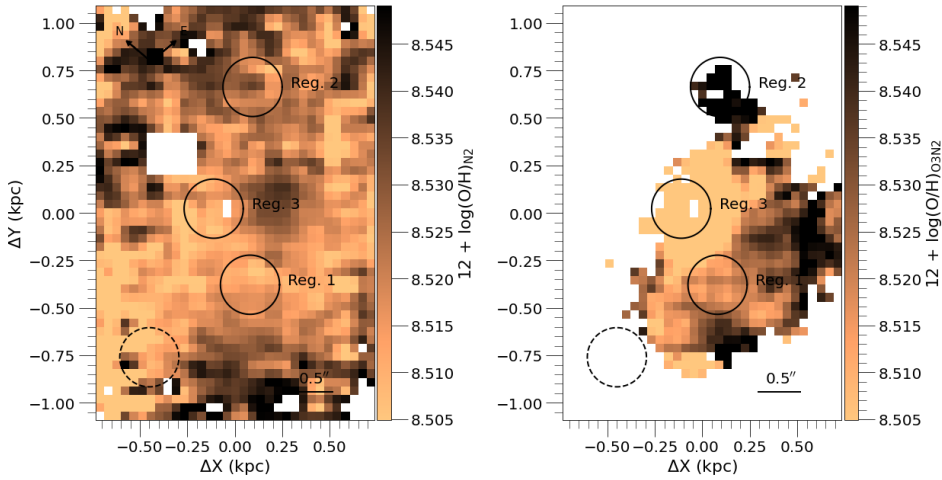
### 3.5. Dating the hinge clump: Observing multiple stellar populations

We used the  $H\alpha$  equivalent width (right panel of Fig. 6),  $EW_{H\alpha}$ , to estimate the ages of the different star-forming clumps that form region ID26. The observed  $EW_{H\alpha}$  were compared with predictions derived from the STARBURST99, SB99 model (Leitherer et al. 1999). These models determine the evolution of different physical parameters for a single stellar population. In the case of the equivalent width,  $EW_{H\alpha, SB99}$ , we compared it with our observations for the instantaneous case with a solar metallicity and a Salpeter (1955) initial mass function (IMF). We note that SB99 models that assume a continuous SFR process display different age evolutions depending on the IMF. Then, considering this issue, and for simplicity, we adopted an instantaneous SFR process without a strong dependence on the IMF. Our results are shown in the top left panel of Fig. 7. As expected from a young star-forming complex, which is dominated by massive star formation, most of the region has ages younger than  $\sim 7$  Myr. The central clump of ID26 (Reg. 3) displays older ages, with a mean age and a standard deviation of  $6.40 \pm 0.04$  Myr. This

<sup>5</sup> <https://gitlab.com/joseaher/astroismlib>



**Fig. 4.**  $H\beta$  and extinction maps of region ID26. Top left panel:  $H\beta$  map. Top right panel:  $H\beta$  tessellation map. Bottom left panel: extinction map in magnitude. Bottom right panel:  $H\alpha$  extinction-corrected map. The flux maps are in  $\times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1} \text{ pixel}^{-1}$  units. The intensities in the maps are shown in different ranges to highlight the substructure in region ID26. The dashed circles in the bottom right corners represent the seeing. The black bar in each panel shows the angular scale. All panels show a white square that masks a set of poor fibers in the IFU/GMOS.



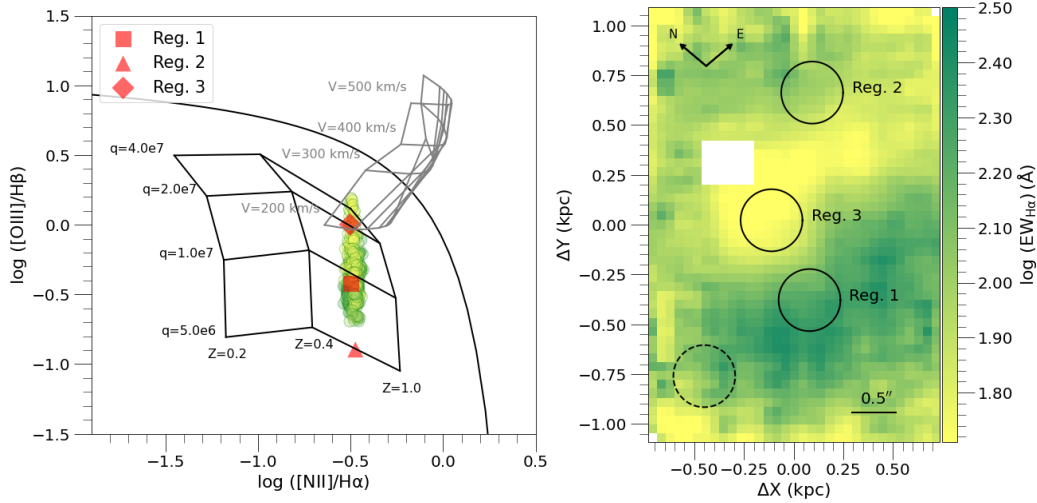
**Fig. 5.** Metallicity maps of region ID26. Left panel: oxygen abundance map estimated from the N2 index (Storchi-Bergmann et al. 1994). Right panel: oxygen abundance map estimated from the O3N2 index (Alloin et al. 1979). The dashed circle in the bottom right corner represents the seeing, and the bar at left-bottom corner is the angular scale. All panels show a white square that corresponds to a poor fiber in the IFU/GMOS.

central region is encompassed by a ring-like structure (dashed red circle) that is younger by about 0.5 Myr. This structure has a radius of about  $\sim 0.67$  kpc. Inside it, lie Reg. 1 and Reg. 2, which exhibit mean ages and standard deviations of  $5.85 \pm 0.08$  and  $6.18 \pm 0.09$  Myr, respectively. We note that our determinations provide an estimate of the age of the last star formation episode. However, no radial age gradient can be confirmed. Smith et al. (2014) claimed that hinge clumps have a range of stellar populations with different ages, suggesting that these objects can be long-lived structures. These authors argued that inflows might feed the star formation. Within the context of an ongoing starburst episode, it is highly plausible that the ring-like structure represents a second generation of star formation, initiated approximately 0.5 Myr later than in the central region as a direct

response to the strong feedback of the central source in ID26. In addition, the BPT analysis indicates that Reg. 3 might be ionized by shocks produced by stellar and supernova winds. These powerful energetic processes can trigger new bursts of star formation. Further evidence supporting this scenario can be obtained from a detailed kinematic analysis of region ID26, which is described in Sect. 4.1.

In order to determine whether region ID26 has different stellar populations, we used archival MUSE data to produce an integrated spectrum of this region and compare it with the Fitting Analysis using Differential Evolution Optimization code<sup>6</sup> (FADO; Gomes & Papaderos 2017). We adopted this strategy

<sup>6</sup> <http://spectralsynthesis.org/index.html>



**Fig. 6.** Ionization mechanism diagnostic diagram of region ID26. Left panel: Ionization mechanism diagnostic diagram in which we plot the emission line flux ratios  $[OIII]/H\beta$  vs.  $[NII]/H\alpha$  for all spaxels covered by the IFU/GMOS FoV. The integrated points (black symbols) correspond to the analyzed Regs. 1, 2, and 3. The spaxel points are color-coded following the  $EW_{H\alpha}$  map (shown in the right panel of this figure). The black and gray grids correspond to the photoionizing and shock-ionizing models, respectively. The grid vertices of photoionizing model were computed in a range of metallicities of 0.2, 0.4, and  $1 Z_{\odot}$ , an ionizing parameter of  $5 \times 10^6$ ,  $1 \times 10^7$ ,  $2 \times 10^7$ , and  $4 \times 10^7$  cm s $^{-1}$ , with an  $N_e$  of  $10$  cm $^{-3}$ , and for an instantaneous burst (Kewley et al. 2001). The grid vertices of the shock-ionizing model were calculated in a range of shock velocities of 200, 300, 400, and 500 km s $^{-1}$ , a magnetic field from left to right of 0.0001, 0.5, 1.0, 2.0, 3.23, 4.0, 5.0, and 10.0  $\mu$ G, with an  $N_e$  of  $1$  cm $^{-3}$ , with a metallicity of  $1 Z_{\odot}$ , and a composition of shock+precursor regions (Allen et al. 2008). As reference, we also display the maximum photoionization line (in black) from Kewley et al. (2001). Right panel:  $EW_{H\alpha}$  map. The dashed circle in the bottom right corner represents the seeing. The bar in the bottom left corner is the angular scale. The white square corresponds to a poor fiber in the IFU/GMOS.

instead of using the Gemini/GMOS data because the latter data were observed with two different gratings (B1200 and R831), which add more complexity to the analysis of stellar populations. In the bottom panel of Fig. 7, we display the result of this approach, where we show the FADO output. The observed spectra (orange line), the best-fitting synthetic SED (light blue line), the contribution of the stellar continuum (dark gray line), and the contribution of the continuum emission spectrum (red line) are shown. Region ID26 can be reproduced by models with a wide age range. It includes models of stellar populations as old as  $\sim 1$  Gyr, as shown in the bottom right panels. A very young stellar population also contributes (a few million years), which is fully consistent with the  $EW_{H\alpha}$  map. All these pieces of evidence indicate that the object ID26 includes different stellar populations and ages. Smith et al. (2014) indicated that hinge clumps are expected to display a range of different stellar populations and ages, given a continuous gas flow. Through numerical simulations, Rodrigues et al. (1999) found that NGC 6845 A and B interacted 150 Myr ago. In this way, the interaction between galaxies could have originated the intermediate-age stellar populations shown in bottom right panels of Fig. 7, following with a new burst of star formation episode through which the young-age stellar populations formed in situ. Finally, the old-age stellar population shown in the bottom right panels of Fig. 7 could correspond to the old-age stellar populations inherited from the disk.

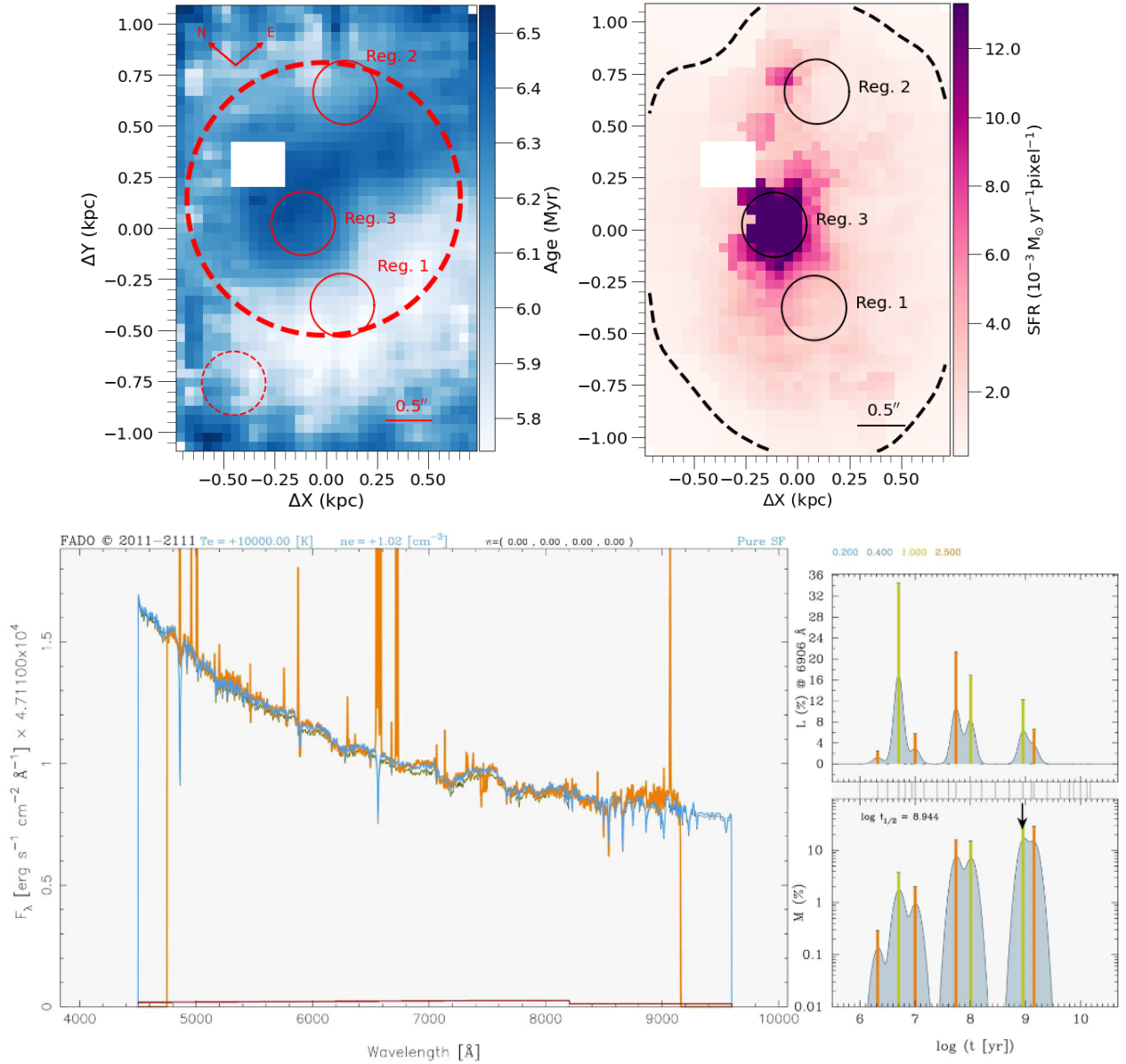
### 3.6. Bright extranuclear burst of star formation

Optical imaging reveals that region ID26 is the brightest source in NGC 6845A. It is even brighter than its central region. This vigorous luminosity is currently associated with a starburst event. In the top right panel of Fig. 7, we show the star formation rate map for this source, which was derived from the  $H\alpha$  luminosity and using Eq. (2) of the calibration proposed by Kennicutt

(1998). In order to compare the SFR of region ID26 with that of other systems (e.g., Smith et al. 2014), we delimited region ID26 inside the isophote at one-hundredth of the peak of  $H\alpha$  map. This boundary is displayed in the SFR map (black contour in Fig. 7) and has an equivalent radius ( $R_{eq}$ ) of  $1.9''$  (equivalent to 0.9 kpc), which was estimated from the area of the isophote at one-hundredth of the peak of  $H\alpha$  map where  $R_{eq} = \sqrt{(Area/\pi)}$ . We obtain an integrated SFR =  $3.4 M_{\odot} \text{ yr}^{-1}$ , which would place region ID26 among the brightest hinge clumps detected so far (it is as bright as the fifth most luminous hinge clumps studied by Smith et al. (2014); see their Table 10). By using the MUSE data, we estimate that hinge clump ID26 accounts for  $\sim 15\%$  of the total star formation in NGC 6845A. This contribution is similar to the contributions found for the hinge clump sample of Smith et al. (2014) (see their Table 10). We note that most of the star formation in ID26 is localized in the central clump of Reg. 3, which contains almost  $\sim 21\%$  of the total SFR of ID26. Using this region, we derived a  $\Sigma = 9.7 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ . This value locates region ID26 in the starburst regime described in (Daddi et al. 2010), where gas inflows are expected to provide gas to maintain the star formation.

Figure 1 shows the 20 cm continuum distribution on the compact group NGC 6845 (black contours taken from Gordon et al. 2003). This figure shows that the 20 cm continuum peaks at the location of the hinge clump. This correlation was found in other hinge clumps. For instance, a hinge clump identified in Arp 256 is bright in the 20 cm continuum (Chen et al. 2002; Smith et al. 2014). In a similar way, the hinge clump called feature i in NGC 2207 (Elmegreen et al. 2006; Smith et al. 2014) is the most luminous radio continuum source in this galaxy (Vila et al. 1990; Kaufman et al. 2012). Kaufman et al. (2012) indicated that non-thermal radio emission is significant in this source. Further studies are needed in order to disentangle the origin of the radio continuum emission in region ID26, given its nature. We cannot discard a supernova remnant in this source. ALMA data can





**Fig. 7.** Top left panel: Ages derived from the H $\alpha$  equivalent width. The bold dashed red circle displays the ring-like structure encompassing the central clump of region ID26. The dashed circle in the bottom right corner represents the seeing area, and the bar in the bottom left corner is the angular scale. Top right panel: star formation rates, based on H $\alpha$  luminosities. The isophote intensity, shown as the dashed black contour, is a hundredth of the peak of the H $\alpha$  map, and delimits region ID26. The top panels show a white square that corresponds to a poor fiber in the IFU/GMOS. Bottom left panel: Standard FADO output of the MUSE-integrated spectra of region ID26 (orange line). In the same spectrum, we plot the best-fitting synthetic SED derived by FADO (light blue line), which is composed of stellar and nebular continuum emission (dark gray and red lines, respectively). In the upper part of that panel, we plot the electronic temperature ( $T_e$ ), electronic density ( $n_e$ ), and the probability ( $\pi$ ) of the spectrum to fall in the locus of star-forming, composite, LINER, and Seyfert galaxies in the BPT diagram. Upper bottom right panel: FADO output plot showing luminosity fractions. The numbers in different colors correspond to different metallicities, and the vertical bars are  $\pm 1\sigma$ . Lower bottom right panel: Stellar mass fraction of the synthetic stellar populations. The thin gray lines connecting both diagrams correspond to the ages of the synthetic stellar populations.

be extremely useful for understanding this intriguing source, in a similar way as was recently done for feature i in NGC 2207 (Kaufman et al. 2020).

## 4. Kinematics of a hinge clump

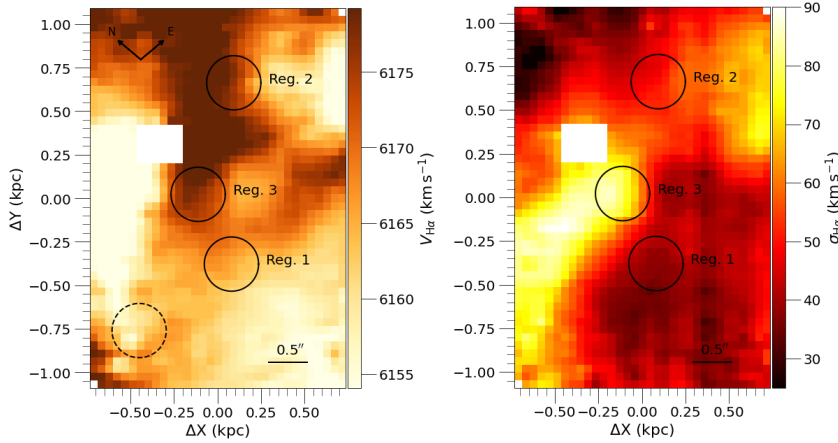
### 4.1. Localized kinematics

Figure 8 shows the H $\alpha$  velocity field ( $V_{\text{H}\alpha}$ ) and H $\alpha$  velocity dispersion map ( $\sigma_{\text{H}\alpha}$ ) for region ID26 (left and right panel, respectively). The velocity dispersion map was corrected for the

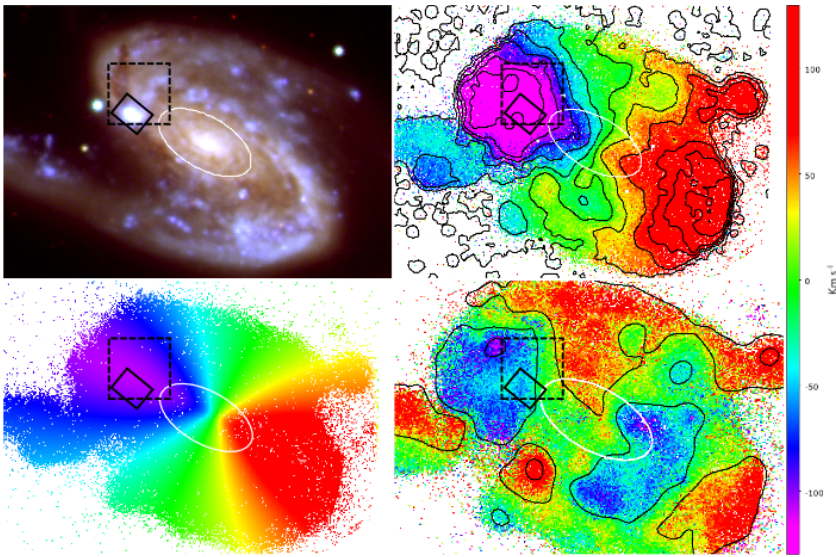
instrumental width, thermal width (9.1 km s $^{-1}$ , O'Dell & Townsley 1988), and natural width (3.0 km s $^{-1}$ , Clegg et al. 1999). The radial velocities in the velocity field are consistent with the values determined by Olave-Rojas et al. (2015) for this region, in the range of 6150 km s $^{-1}$ –6180 km s $^{-1}$ . The entirety of region ID26 shows a very perturbed velocity pattern, which is likely attributable to the ongoing and intense star-forming processes within, which imprints noncircular motions on the local kinematics.

The  $\sigma_{\text{H}\alpha}$  map of region ID26 displays values from 30 km s $^{-1}$  to 90 km s $^{-1}$ . In general, HII regions in disk galaxies display





**Fig. 8.** Velocity maps of region ID26. Left panel: velocity field near the hinge clump. This map was derived from a single Gaussian fit on the  $H\alpha$  emission line observed with Gemini/GMOS. Right panel:  $H\alpha$  velocity dispersion map of the same region as shown in the left panel. The top two panels show a white square that corresponds to a poor fiber in the IFU/GMOS.



**Fig. 9.** Different maps of NGC 6845. Top left: false-color optical Gemini image. The white ellipse represents the region that follows circular motions in the velocity field (top right panel). Top right:  $H\alpha$  velocity field. Bottom left: modeled velocity field. Bottom right: residual velocity field, derived from the observed and modeled velocity field. The bar scale represents the velocities in  $\text{km s}^{-1}$  of the residual map. The black box corresponds to the IFU/GMOS FoV, and the dashed black box corresponds to the area shown in Fig. 10.

velocity dispersion of about  $10\text{--}30 \text{ km s}^{-1}$  (Epinat et al. 2010; Law et al. 2021). The higher velocity dispersion in region ID26 could be attributed to the ongoing starburst process, where shocks and the feedback from massive stars contribute to driving the velocity dispersion up (e.g., Relaño & Beckman 2005; Genzel et al. 2008; Rich et al. 2011, 2015). The mean values (and standard deviations) of  $\sigma_{H\alpha}$  for Regs. 1, 2, and 3 are  $53 \pm 2$ ,  $62 \pm 3$ , and  $84 \pm 7 \text{ km s}^{-1}$ , respectively. The central clump is located in a zone characterized by even higher  $\sigma_{H\alpha}$  values that exceed  $70 \text{ km s}^{-1}$  and looks like a finger. This region runs through Region ID26 from west to east, effectively piercing the ring-like structure identified in the equivalent width map (see the top left panel of Fig. 7). Figure 2 shows the  $H\alpha$  line profile for the central spaxel of Reg. 1. This profile exhibits a broader base that deviates from the fitted Gaussian profile. This feature serves as a signature of the underlying high-velocity components throughout the entire Region ID26 (e.g., Relaño & Beckman 2005; Firpo et al. 2010, 2011). However, the current GMOS spectral resolution does not allow us to perform a detailed multicomponent analysis of these profiles.

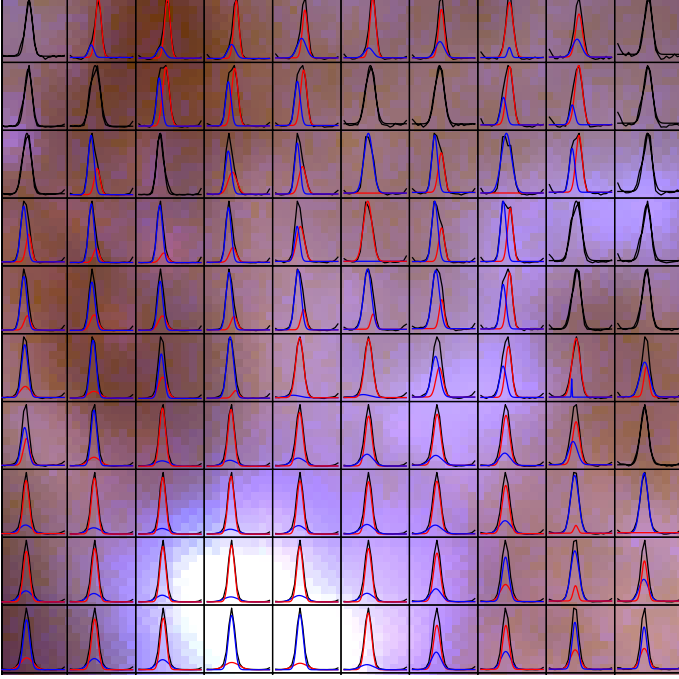
#### 4.2. Larger context: MUSE insight

Unfortunately, the small FoV of the Gemini data prevents a detailed discussion of the origin of region ID26, such as whether it is an accreting satellite or a local hinge clump. To address this

question, we modeled the whole velocity field of NGC 6845A with MUSE archival data. From this, we derived the  $H\alpha$  velocity field of NGC 6845A by fitting a single Gaussian on the  $H\alpha$  lines over the data cube by using the ASTROCUBELIB code. In the top panels of Fig. 9, we show the Gemini optical image of NGC 6845A and its velocity field (top left and top right panels, respectively). As a reference, we overplot the isovelocitys on the velocity field. The central region of NGC 6845A displays the typical rotation-like pattern of a disk galaxy, which can be seen in the isovelocitys. This region is highlighted with a white ellipse, which has a semimajor axis of  $8.9 \text{ arcsec}$ , equivalent to  $4.3 \text{ kpc}$ . From this radius deviates a purely circular motion, showing a vertical perturbation that appears to be associated with a warp. A visual inspection of the Gemini image shows a warp-like structure in the southwest region of NGC 6845A, where the extended southern tidal tail of NGC 6845A starts as well.

For region ID26, the MUSE velocity field shows a perturbed behavior, but this region seems to be in the plane of the disk. In order to confirm this scenario, we modeled the observed velocity field following the same method as proposed by Hernandez-Jimenez et al. (2013, 2015), which is particularly well suited for interacting systems and the PYTHON package ASTROMODELINGLIB<sup>7</sup> (Hernandez-Jimenez 2024c).

<sup>7</sup> <https://gitlab.com/joseaher/astromodellinglib>



**Fig. 10.**  $H\alpha$  profiles in the region of the hinge clump. Each box represents an angular size of 1 arcsec, where the emission profile was integrated in this area. Asymmetric and double profiles can be identified at the north of the hinge clump ID26. We fit two Gaussians profiles on the observed emission, which are represented by blue and red profiles on each spaxel. North of the hinge clump, these components have a velocity difference of about  $160 \text{ km s}^{-1}$ .

First, we performed a two-dimensional modeling for the light distribution of NGC 6845A. This modeling was based on the GMOS  $r'$ -band image, and it includes a bulge (Sersic 1968; Peng et al. 2010), a bar (utilizing a 2D Ferrers modified profile, Binney & Tremaine 2008; Peng et al. 2010), and a disk (Freeman 1970; Peng et al. 2010). Subsequently, we transformed the two-dimensional fitted disk profile, which represents the dominant stellar mass component of the galaxy, into its corresponding mass density profile, assuming a constant mass-to-light ratio. To derive this constant, we used the integrated color ( $g - r$ ) up to two effective radii of NGC 6845A and the coefficients provided in Table 7 of Bell et al. (2003). The halo component was modeled using a Navarro-Frenk-White (NFW) profile (Navarro et al. 1995). Afterward, the observed velocity field was fit letting the halo parameters free, that is, the kinematic center and the position angle of the line of nodes. The modeled velocity field is shown in the bottom left panel of Fig. 9. Finally, the modeled velocity field was subtracted from the observed one, producing a residual velocity field. This is shown in the bottom right panel of Fig. 9, where we include its isovelocitys. Large velocity deviations can be observed in this residual map, especially in the locations of the vertical perturbations and north of the hinge clump. In particular, the hinge clump displays a radial velocity of  $6152 \text{ km s}^{-1}$ , which is  $\sim 30\text{--}40 \text{ km s}^{-1}$  bluer than the velocity of the modeled velocity field at that location. The velocity difference is even larger north of the hinge clump, where it reaches values of  $\sim 100 \text{ km s}^{-1}$  in the residual velocity map. However, these perturbations are still compatible with the observed perturbations over the entire field.

Therefore, the velocity field suggests that region ID26 follows the kinematics of the disk of NGC 6845A, enforcing the

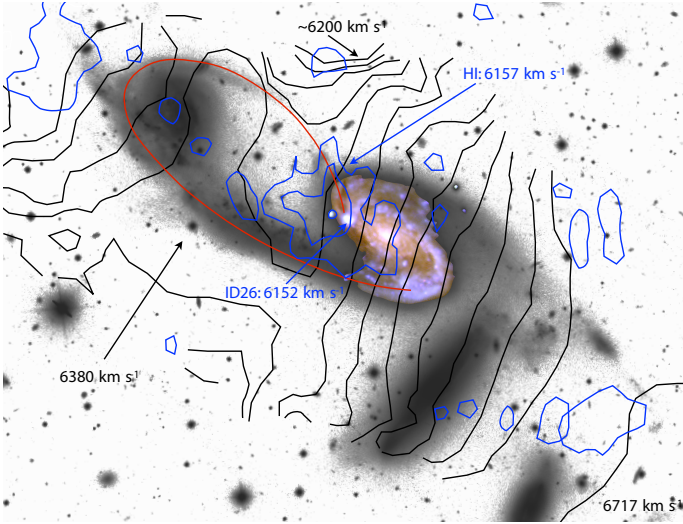
hinge clump scenario, according to which, this object was formed in the disk of the main galaxy, in this case, at the base of the northern tidal tail, due to gas inflows produced by orbital crowding (see Struck & Smith 2012). The optical images display some warp-like features on the disk of NGC 6845A, and it displays extended tidal tails, which seem to lie beyond the plane of the galaxy. In addition, the H I channels maps displayed by Gordon et al. (2003) showed some neutral gas at the location of the hinge clump. This H I emission was detected to start at the same radial velocity as our optical spectra,  $v_{\text{HI}} \sim 6157 \text{ km s}^{-1}$ . This H I detection is blueshifted with respect to the whole H I emission of this system, as shown in Fig. 10 of Gordon et al. (2003), where they display the whole velocity field for this object. Then, the neutral gas kinematics seems to be compatible with the kinematics derived from the ionized gas.

In order to explore the kinematic of the warm gas around the hinge clump in more detail, we show in Fig. 10 the  $H\alpha$  profiles of the northern region of NGC 6845A, overplotted on the optical Gemini/GMOS image. Each box has a size of 1 arcsec, where the profile represents the sum of the different  $H\alpha$  profiles on this box (MUSE pixel size of  $0.2 \text{ arcsec pixel}^{-1}$ ). Figure 10 reveals a diversity in the profile shape. In general, the observed profiles trace the velocity field shown in Fig. 9. However, north of the hinge clump, we detect asymmetric profiles, which can affect the determination of the velocity field. Double  $H\alpha$  profiles can be identified. Different interacting systems display double or complex  $H\alpha$  profiles (e.g., Amram et al. 2004 for HCG 31, Repetto et al. 2010 for NGC 5278/79), which are typically associated with gas flows and/or are produced by the geometry of the system. To determine the radial velocity of the  $H\alpha$  components, we deblended the emission line based on the  $H\alpha$  emission line. We found a typical velocity difference of  $\sim 160 \text{ km s}^{-1}$  among the two components. In Fig. 10 we highlight in a schematic way the two components that can be identified in some spaxels. Blue and red Gaussian profiles represent the two components. Our finding suggests that one component (redshifted) is associated with the kinematics of the disk, and the other component (blueshifted) is associated with a star formation event that occurs due to some extraplanar gas that falls into the disk of NGC 6845A. This scenario is consistent with the H I detection described above. Another interacting system that displays similar features is NGC 2207 (Kaufman et al. 2020), for example. In the hinge clump in NGC 6845A, we witness a strong star formation event in the form of a hinge clump, which is enhanced due to the accretion of gas.

## 5. Other pieces of evidence to explain the formation of the hinge clump

In the case of NGC 6845A, Fig. 1 reveals extended tidal tails. As explained above, we suggest that the hinge clump has enhanced its star formation due to some extraplanar gas flow into the disk of NGC 6845A. In Fig. 11 we show a high-contrast image of NGC 6845A, where we designed a schematic representation of the eastern tidal tail of NGC 6845A, which follows the faint stellar feature associated with the tidal tail (red line). In the same figure, we include the H I isovelocitys (taken from Gordon et al. 2003), which are represented by black lines. We also include the H I emission detected at  $6157 \text{ km s}^{-1}$  (blue contours), as shown in Fig. 2 of Gordon et al. (2003). We include this latter H I emission because its radial velocity is similar to that of the hinge clump. Figure 11 significantly enriches the discussion that aims to understand the origin of region ID26. The detection of some neutral gas at  $6157 \text{ km s}^{-1}$  (blue contours) suggests that





**Fig. 11.** Gemini/GMOS  $r'$ -band of NGC 6845. The black contours show the isovocities analyzed by [Gordon et al. 2003](#). The blue contours indicate the H I distribution at the velocity of  $6152 \text{ km s}^{-1}$ , as shown in Fig. 2 of [Gordon et al. 2003](#). The red line shows the position of the optical tidal tail of NGC 6845A.

extraplanar gas falls into the disk of NGC 6845A. In addition, we cannot discard that the eastern tidal tail of NGC 6845A reaches several kiloparsecs and falls into its own disk, as represented by the red line in Fig. 11. This process can produce a gas flow into the hinge clump, enhancing the star formation at this location. NGC 6845B displays a radial velocity of about  $6800 \text{ km s}^{-1}$ , and therefore, the scenario proposed for the extended tidal tail can support the current observations.

In addition, the metallicity of Region ID26 is higher than the metallicity of the regions in the tidal tails of NGC 6845A, and it is comparable to the metallicity of the regions in the disk of NGC 6845A (see [Olave-Rojas et al. 2015](#)). Moreover, [Olave-Rojas et al. \(2015\)](#) found that the oxygen abundance of NGC 6845A is lower than expected for its mass and that it has a flat metallicity gradient along its eastern tidal tail. As is shown by several authors (e.g., [Rupke et al. 2010](#); [Torrey et al. 2012](#); [Gao et al. 2023](#)), this result could be due to the star formation events and galactic winds triggered by the interaction/merger between galaxies. In this context, [Rodrigues et al. \(1999\)](#) used numerical simulations that suggested that NGC 6845A interacted with NGC 6845B  $\sim 150 \text{ Myr}$  ago. Based on the results of [Olave-Rojas et al. \(2015\)](#), we suggest that the interaction between these systems produced an inflow of pristine gas that diluted the metallicity content in the original gas of NGC 6845A. This flattens the metallicity gradient and enhances the star formation activity of this system.

## 6. Conclusions

We reported the physical and kinematical properties of a hinge clump located in the compact group of galaxies NGC 6845. The hinge clump, called ID26, is located in projection at the base of a tidal tail, in agreement with previous modeling that explained the origin of these sources ([Struck & Smith 2012](#)). In addition, kinematic data allowed us to rule out a possible scenario in which region ID26 was a satellite galaxy. Its kinematics is consistent with the kinematics of the galactic disk of NGC 6845A. The local metallicity abundance is also consistent with the metallicity gradient of the galaxy ([Olave-Rojas et al.](#)

[2015](#)). ID26 is composed of a strong H $\alpha$  emitting source that mimics an extranuclear starburst. ID26 represents  $\sim 15\%$  of the total SFR of NGC 6845. The high-resolution image from HST reveals that ID26 is composed of several knots with a dominant compact source located close to the center of the H $\alpha$  emitting region. This compact source has a physical size of  $70 \text{ pc}$ , as derived from the HST image. Region ID26 has an integrated SFR =  $3.4 M_{\odot} \text{ yr}^{-1}$ , which is comparable with a few other extreme cases, for instance, sources in the Antennae galaxy [He et al. 2022](#) and a few other hinge clumps [Smith et al. \(2014\)](#). A stellar population analysis of its integrated spectra suggests that the hinge clump is formed by multiple stellar populations and not by a single burst because it has a wide range of ages. This is consistent with the multiple stellar populations that are seen in different star clusters. The analysis of the diagnostic diagram also indicates that the central region can also be ionized by shocks from stellar and supernova winds. These powerful energetic processes are not only able to ionize the surrounding environment, but also act as triggers for subsequent bursts of star formation. Further pieces of evidence supporting this scenario are the high values of the velocity dispersion, which range from  $30$  to  $90 \text{ km s}^{-1}$  across this star-forming region, as also found in other star-forming systems (e.g., [Relaño & Beckman 2005](#); [Genzel et al. 2008](#); [Rich et al. 2011, 2015](#)).

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