Evidence for ram pressure stripping in a cluster of galaxies at $z = 0.7$ *

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ABSTRACT

MUSE observations of the cluster of galaxies CGr32 ($M_{200} \approx 2 \times 10^{14} M_\odot$) at $z = 0.73$ reveal the presence of two massive star forming galaxies with extended tails of diffuse gas detected in the [Oiv]λλ3727-3729Å emission-line doublet. The tails, which have a cometary shape with a typical surface brightness of a few $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, extend up to $\approx 100$ kpc (projected distance) from the galaxy discs and are not associated to any stellar component. All this observational evidence suggests that the gas has been removed during a ram-pressure stripping event. This observation is thus the first evidence that dynamical interactions with the intracluster medium were active when the Universe had only half of its present age. The density of the gas derived using the observed [Oiv]λλ3727/[Oiv]λλ3726 line ratio implies a very short recombination time, suggesting that a source of ionisation is necessary to keep the gas ionised within the tail.

Key words. Galaxies: clusters: general; Galaxies: clusters: individual: CGr32; Galaxies: evolution; Galaxies: interactions; Galaxies: ISM; Galaxies: high-redshift

1. Introduction

Since the seminal work of [Dressler]1980 it became evident that the environment plays a major role in shaping galaxy evolution. High density regions such as rich clusters of galaxies are mainly composed of early-type objects (ellipticals and lenticulars) while the field is dominated by late-type, star-forming systems. In these dense regions the fraction of quiescent galaxies increases with decreasing redshift (e.g. [Dressler]1980). It is still unclear which, among the different mechanisms proposed in the literature - gravitational interactions ([Merritt]1983, [Byrd & Valtonen]1990, [Moore et al.]1998) or hydrodynamic interactions with the hot ($T \approx 10^7-10^8$ K) and dense ($\rho_{\text{ICM}} \approx 10^{-3}$ cm$^{-3}$, e.g. [Sarazin]1986) intracluster medium (ICM; [Gunn & Gott]1972, [Cowie & Songaila]1977, [Nulsen]1982, [Larson et al.]1980) - whose contribution might change at different cosmic epochs, is at the origin of these observed differences ([Boselli & Gavazzi]2006, 2014).

In the local Universe, where high sensitivity multi-frequency observations are available, allowing the detection of the different stellar components and gas phases (cold, ionised, hot) with a spectacular angular resolution, it is becoming evident that within structures as massive as $M_{200} \geq 10^{14}$ M$_\odot$ ram pressure stripping is the dominant process responsible for the quenching of the star formation activity of disc galaxies ([Boselli & Gavazzi]2006).

The most convincing evidence comes from the recent very deep observations of nearby clusters using narrow-band filters centred on the Hα Balmer recombination line which revealed the presence of extended (up to $\approx 100$ kpc) low surface brightness ($\Sigma$(Hα) $\approx 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) tails of ionised gas. The cometary shape of the tails and the lack of any associated diffuse tidal structure rule out any gravitational perturbation which would affect at the same time the gaseous and the stellar component. This undoubtedly states that the ionised gas tail formed after the interaction of the galaxy interstellar medium (ISM) with the ICM. The most striking examples have been found first in the nearby cluster A1367 by [Gavazzi et al.]2001 (see also [Boselli & Gavazzi]2014, [Gavazzi et al.]2017) and are now becoming common in other clusters such as [Norma]2013, [Coma]2007, 2010, 2017, [Fossati et al.]2012, [Gavazzi et al.]2018 and Virgo ([Yoshida et al.]2002, [Kenney et al.]2008, [Fossati et al.]2016, 2018b).

Tails of stripped material have been observed also in H1 ([Chung et al.]2007, [Scott et al.]2012), in CO ([Jáchym et al.]2013, 2014, 2017), and in X-rays ([Sun et al.]2006, 2007, 2010), indicating that the other gas phases can also be perturbed during the interaction. Ram pressure stripping as the dominant mechanism is also suggested by the relative distribution in clusters of gas deficient and star forming galaxies ([Gavazzi et al.]2013, [Boselli et al.]2014), by the outside-in radial truncation of the different components of the ISM ([Cayatte et al.]1990, 1994, [Cortese et al.]2010, 2012, [Boselli et al.]2014a) and of the star forming disc

* Based on observations made with ESO telescopes at the Paranal Observatory under programs 097.A-0254, 100.A-0607, 101.A-0282.
The statistical importance of ram pressure stripping, which is proportional to \( \rho_{\text{ICM}} V^2 \) (where \( V \) is the velocity of the galaxy within the cluster and \( \rho_{\text{ICM}} \) is the density of the ICM), is expected to reduce at earlier epochs, when clusters of galaxies were first assembling through the accretion of smaller groups (Gnedin 2003; De Lucia et al. 2012). Here the reduced density of the ICM and lower velocity dispersion typical of lower mass dark matter halos would rather have favoured gravitational interactions able to modify the structural properties of the perturbed galaxies. These gravitationally perturbed objects are probably the progenitors of massive lenticulars observed in nearby clusters (e.g. Boselli & Gavazzi 2006). The transformation of galaxies at higher redshift via gravitational perturbations in lower density structures before their accretion into massive clusters (pre-processing) is also corroborated by the typical age of the stellar populations of lenticulars, by their perturbed star formation history, and by their distribution in high-density regions at different epochs (Dressler et al. 1997, Dressler 2003, Poggianti et al. 1999).

Despite the aforementioned evolutionary picture is now becoming clearer, we still do not know at which epoch and under which conditions gravitational perturbations are superseded by hydrodynamic interactions of galaxies with the ICM. Although massive clusters were significantly less numerous in the past, the physical conditions encountered by infalling systems were similar to those present in local clusters, characterised by similar \( \rho_{\text{ICM}} \) gas densities (Giodini et al. 2013, McDonald et al. 2017). It is thus conceivable that ram pressure episodes were already present at early epochs. Because of obvious observational limits, direct evidence for ongoing ram pressure stripping at higher redshift is still lacking. Cortese et al. (2007) discovered two galaxies in two clusters at \( z \approx 0.2 \) with extended tails of star forming regions, now generally referred to as jellyfish galaxies (e.g. Poggianti et al. 2017). Since then, another ~ fifty objects with similar characteristics have been found in deep HST images of clusters at \( 0.3 \leq z \leq 0.7 \) (Owers et al. 2012, Ebeling et al. 2014, McPartland et al. 2016). Since selected in the optical bands, however, where the emission is dominated by stars of intermediate age, a jellyfish morphology is not a direct proof of an ongoing ram pressure stripping episode (Cortese et al. 2007). Indeed, in ram pressure stripped galaxies star formation in the tail is not ubiquitous (e.g. Boselli et al. 2016b), and whenever observed, it is generally localised in very compact H\(_{\text{II}}\) regions dominated by young stellar populations emitting mainly in the UV bands. Extended and asymmetric low surface brightness structures in the optical bands are due to tidal tails. The only clear example of galaxies undergoing ram pressure stripping at intermediate redshift comes from deep Subaru narrow-band imaging observations of the cluster Abell 851 at \( z=0.4 \) (Yagi et al. 2015). Indirect evidences at \( z=0.7 \) comes from the reduced gas content (Betti et al. 2019) and from the extended \( H\alpha \) ionised gas emission (Valc天空a et al. 2016) observed in galaxies located in high-density regions.

The search for galaxies undergoing a ram pressure stripping event in high-\( z \) clusters is now possible thanks to the advent of new generation instruments in the radio millimetric and in the optical domain. The extraordinary sensitivity of ALMA allows the detection of low column density tails of molecular gas stripped from perturbed cluster galaxies. The results obtained in the local Universe, however, suggest that the cold gas, once stripped and in contact with the hot surrounding ICM, rapidly changes phase becoming ionised via different possible mechanisms such as heat conduction, shocks, or magneto hydrodynamic waves (Tomesen & Bryan 2010, 2012. Boselli et al. 2016a, Gavazzi et al. 2018). The ionised gas phase can be detected by IFU spectrographs provided that their sensitivity is sufficient to reach surface brightnesses as low as \( \sim 10^{-18} \) erg cm\(^{-2}\) arcsec\(^{-2}\), the typical limiting surface brightness of MUSE after \( \sim 1 \) h of exposure.

As part of the MUSE Guaranteed Time Observations (GTO), we have recently undertaken a spectroscopic survey of intermediate redshift (0.25 < \( z \) < 0.85) groups and clusters (MAGIC: MUSE-gAlaxy Groups In CosmS, Epinat et al. in prep). During this survey we detected two star forming galaxies in the COSMOS cluster 32 (Knobel et al. 2012) at \( z=0.73 \) with extended (up to \( \sim 100 \) kpc in projected distance) tails of ionised gas without any stellar counterpart in the deep optical images. This observation is thus the first evidence of an ongoing ram pressure stripping event at \( z > 0.5 \). This paper is structured as follows: in Sect. 2 we briefly describe the cluster, in Sect. 3 the observations and the data reduction. The analysis of the MUSE data is given in Sect. 4, and the results are discussed in Sect. 5 and summarised in the conclusions. We assume a \( \Lambda \)CDM cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.7 \), and \( \Omega_\Lambda = 0.3 \).

### 2. The galaxies ID345 and ID473 in the cluster CGr32

Initially identified as a group, the COSMOS cluster 32 (CGr32; Knobel et al. 2012) shows properties typical of cluster of galaxies. CGr32 is located at a redshift of \( z=0.73 \) and is part of the COSMOS Wall described by Kovino et al. (2016) (see Fig. 1). Thanks to the new MUSE observations 105 galaxies have been identified as cluster members. We determined cluster membership based on the spatial and redshift distributions thanks to a friends-of-friends algorithm using a linking length of 450 kpc and a velocity separation of 500 km s\(^{-1}\) (Epinat et al., in prep.). The cluster has a velocity dispersion of \( \sim 930 \) km s\(^{-1}\) using all galaxies detected with MUSE, a radius \( R_{200} \approx 1 \) Mpc, and a dynamical mass \( M_{200} \approx 2.3 \times 10^{14} \) M\(_{\odot}\) inferred from X-rays observations (ID 10220 in Gozaliasl et al. 2019) and is thus comparable to a fairly massive cluster such as Virgo in the local Universe. The fraction of star forming galaxies (~50%) is close to the typical fraction observed in similar clusters at that redshift (Dressler 1997) and to that of the spiral-rich Virgo cluster (48%, Boselli et al. 2014b). The galaxies studied in this work (ID345 and ID473) are two edge-on spirals located at ~200-220 kpc from the cluster centre (see Table 2) coherently identified as the peak of galaxy and of hot gas density in both the MUSE data (Epinat et al., in prep.) and in the XMM-Newton/Chandra X-rays data (Finoguenov et al. 2007, George et al. 2011, Gozaliasl et al. 2019) and this work – see Table 2 and Sect 3.2. The asymmetric velocity distribution of galaxy members and a significantly larger velocity dispersion of the star forming galaxies \( \sigma_{\text{V}} = 1085 \) km s\(^{-1}\) with respect to the quiescent objects \( \sigma_{\text{Q}} = 697 \) km s\(^{-1}\) suggest infall into the cluster (Colless & Dunn 1996), as indeed expected for a cluster still in formation (Fig 2). The galaxies ID345 and ID473 (Fig. 3) have a relative line-of-sight velocity with respect to the cluster of \( V_{\text{rel}} \approx -824 \) km

\(^{1}\) The distinction between quiescent and star-forming galaxies is performed from their distribution in the main sequence diagram as suggested by Barro et al. (2017), and consistently with Boselli et al. (2014b). Stellar masses and star formation rates have been derived as described in Sect. 3.2.
Table 1. Properties of the cluster CGr32

| Variable | Value | Ref. | Comment |
|----------|-------|------|---------|
| R.A. (J2000) | 149°55'19.0" | TW | MUSE barycentre |
| Dec. (J2000) | 2°31'15.5" | TW | MUSE barycentre |
| R.A. (J2000) | 149°55'14.8" | 1 | from X-rays data |
| Dec. (J2000) | 2°31'18.0" | 1 | from X-rays data |
| z | 0.7303 | 1 |
| σ | 931 km s\(^{-1}\) | TW | full sample |
| σ\(_Q\) | 697 km s\(^{-1}\) | TW | quiescent galaxies |
| σ\(_S\) | 1085 km s\(^{-1}\) | TW | star forming galaxies |
| R\(_{200}\) | 1.53 Mpc | TW | from MUSE data |
| M\(_{200}\) | 8.14 \times 10^{14} M\(_{\odot}\) | TW | from MUSE data\(^a\) |
| M\(_{200}\) | 0.983 Mpc | 1 | from X-rays data |
| M\(_{200}\) | 2.33 \times 10^{14} M\(_{\odot}\) | 1 | from X-rays data |

References: TW: this work, 1) Gozaliasl et al. (2019).

\(^a\): This mass reduces to \(M_{200} = 3.41 \times 10^{14} M_{\odot}\) if derived using the velocity dispersion of the quiescent population only rather than the full sample.

\(\Delta V_{ID373} = -1903\) km s\(^{-1}\), and are thus crossing the cluster from the back. Despite its large line-of-sight velocity, ID473 has a high probability to be a real member of the cluster. Indeed, using more stringent parameters for the friends-of-friends algorithm as low as 375 kpc and 400 km s\(^{-1}\), as suggested by Iovino et al. (2016), it still remains a member.

3. Observations and data reduction

3.1. MUSE spectroscopy

Details of the MUSE observations and data reduction will be presented in a dedicated paper (MAGIC survey paper, Epinat et al. in prep). Here we briefly summarise the main steps. The observations of CGr32 were obtained during MUSE-GTO as part of the MAGIC project (Epinat et al. in prep, PI: T. Contini). Three fields were necessary to map the cluster core. An equal observing time of 4.35h was spent on each field over three observing blocks, which were not used to produce integrated spectra (and their variance spectra) for both galaxies and associated tails (cf. Fig. 5). The velocity amplitude over these galaxies and tails is \(\sim 400\) km s\(^{-1}\), which would broaden emission lines in the spectra integrated over the masks and thus decrease the signal to noise ratio. Therefore, in order to remove large scale velocity variations, each pixel is set, before integration, at rest wavelengths using the spatially resolved velocity field shown in Fig. 2. The residual broadening due to the uncertainties in the velocity field is \(\sim 30 - 50\) km s\(^{-1}\), which reduces the spectral resolution of the MUSE data (see Bacon et al. 2017) over the whole spectral range shown in Fig. 3. The continuum due to the bright star was removed from the galaxy ID473 and its tail spectra by scaling the absorption lines of the star spectrum. For the tail a residual continuum signal due to both the star and a background galaxy was also removed. In the tails the [O\(_{\text{II}}\)] doublet and its uncertainty was then measured as the sum of the spectra around a narrow spectral window centred on the line which corresponds to a velocity amplitude of 600 km s\(^{-1}\) around each side of the lines. Uncertainties were determined over the same range from the variance spectrum. The observed fluxes in the tails are given in Table 2. We also measured the mean [O\(_{\text{II}}\)] doublet ratio within the tail. The mean ratio in the tail of ID345, the only one where the signal is sufficiently high to make this velocity correction possible, is \([\text{[O}\_\text{II}]/\text{[O}\_\text{III}] = 1.15 \pm 0.06\). We recall, however, that this is a light-weighted mean, probably biased towards the emission of the brightest regions, possibly associated to compact but unresolved H\(_{\text{II}}\) regions.

For each of the three fields, we produced a single reduction combining all exposures with and without AO. The reduction was performed using the MUSE standard pipeline v1.6 (Weilbacher et al. 2012, 2014, 2015). The data reduction process generates data cubes with a spatial sampling of 0.2'' and a spectral sampling of 1.25 Å. The spatial extent of each field is of one square arcminute and the spectrum ranges from 4750 Å to 9350 Å.

The point spread function (PSF) of the combined exposures was estimated on each field from a Gaussian fit to the stars present in each datacube. The average full width at half maximum (FWHM) at \(\lambda = 6450\) Å ranges from 0.60'' to 0.72'' depending on the field. The two galaxies with tails are visible on the same field which has a FWHM of 0.60''.

We derived [O\(_{\text{III}}\)] flux (Fig. 3) and kinematics (Fig. 4) maps for the two galaxies with tails using CAMEl (Epinat et al. 2012), which fits any emission line using a Gaussian function and a polynomial smoothing to any pixel of a datacube, after a Gaussian spatial smoothing with a FWHM of 3 \times 3 pixels and using a continuum of degree one, mainly to account for the continuum of the strong star in the field which is close to the two galaxies. We also extracted the same maps with a Gaussian spatial smoothing of \(4 \times 4\) pixels FWHM in order to define masks where the tails are detected in [O\(_{\text{II}}\)]. The masks were defined using both a flux threshold of \(7.5 \times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) (1.5 times the surface brightness limit in the smoothed [O\(_{\text{II}}\)] map) and a criterion on kinematics of the detected structure to remove regions with velocity discontinuities larger than \(\sim 200\) km s\(^{-1}\). An additional mask was applied to hide the emission from other galaxies in the group. These final masks were used to produce integrated spectra (and their variance spectra) for both galaxies and associated tails (cf. Fig. 5).

\(^2\) Hereafter [O\(_{\text{II}}\)] refers to the [O\(_{\text{II}}]/\text{[O}\_\text{III}] = 7.76 \pm 0.25 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\), and an upper limit in the tail of ID473 (\(\sigma_{\text{[O}\_\text{II}] ol}\) = 1.92 \times 10^{-18} erg s\(^{-1}\) cm\(^{-2}\)), as well as upper limits in both tails for the [O\(_{\text{II}}\)] line (\(\sigma_{\text{[O}\_\text{II}] ol}\) = 5.23 and \(\sigma_{\text{[O}\_\text{II}] ol}\) = 2.03 in units of \(10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\)).

\(^3\) https://gitlab.lam.fr/bepinat/CAMEL.git
3.2. Other data

CGr32 is inside the COSMOS field (Scoville et al. 2007) and has therefore been observed in many bands. We used the HST-ACS image of the field observed with the F814W filter for a morphological analysis of the two galaxies with GALFIT (Peng et al. 2002), while the Subprime/Subaru camera image in the i-band (Taniguchi et al. 2007), the deepest available for this field with a limiting surface brightness of 28 mag arcsec$^{-2}$, was used to search for any possible red stellar population counterpart in the galaxy tails. We also used the XMM-Newton data for the determination of the density profile of the hot ICM. For this purpose we used the COSMOS mosaic image in the 0.5 to 2 keV band (Hasinger et al. 2007; Finoguenov et al. 2007) for illustration purposes in Fig. 1 and the OBSID 0203361701 archive data for the extraction of the hot gas density distribution. This is the longest exposure (∼32 ksec) covering CGr32 within the inner 10 arcmin of the FoV. The data were processed following the methodology presented in Pratt et al. (2007) and Bartalucci et al. (2017). The 3D density profile is derived from the surface brightness profile (extracted at the position of the X-ray centre...
reported in Table 1 using a non-parametric deconvolution and deprojection method with regularisation (Croston et al. 2006) – see Fig. 6 and Sec. 5.

We determined galaxy parameters, such as stellar mass, star formation rate (SFR), and extinction, from spectral energy distribution models using the FAST code (Kneib et al. 2009) as described in Epinat et al. (2018) for a similar dataset in the COSMOS field with deep imaging data from the UV to the near-IR. Stellar masses and SFR are calculated assuming a Chabrier (2003) IMF. The spectrum of ID345 exhibits asymmetric shapes of the emission lines [O III] 5007, 5007 and H β which could be explained by a contribution from an AGN. The presence of an AGN is also suggested by its strong observed radio emission at 1.4 GHz (0.115 mJy – Schinnerer et al. 2010 – corresponding to a rest frame luminosity $L(1.4 \text{GHz}) = 4 \times 10^{23} \text{ W Hz}^{-1}$ derived assuming a nonthermal spectral index $\alpha = 0.8$ – Condon 1992). Should such an AGN indeed be present, this could bias the SFR derived from SED fitting. For the galaxy ID473, where the photometry is highly contaminated from a nearby star, the stellar mass is just a rough estimate. For this galaxy the SFR is determined using two different methods, the first one from the H β emission line corrected for dust attenuation using the Balmer decrement, the second one from the observed [O III] line using the calibration of Moustakas et al. (2006).

4. Analysis

4.1. Physical properties

The MUSE observations of the cluster reveal the presence of an extended tail of ionised gas detected in the [O III] line associated with the two galaxies ID345 and ID473, as depicted in Fig. 3. The two tails, which extend from the galaxy discs in the south-east direction, are 13.4′′ (97 kpc) and 4.7′′ (34 kpc) long (projected distance) and 2.9′′ (21 kpc) and 2.1′′ (15 kpc) wide (see Table 2). The deep optical images of the cluster do not show any stellar counterpart associated to the extended ionised gas tail (Fig. 3) down to a surface brightness limit of $\approx 28 \text{ mag arcsec}^{-2}$ in the $i$-band. The orientation of the tails, which in both cases is parallel to the stellar disc major axis, also indicates that the gas stripping is occurring edge-on. Figure 5 shows the spectra of the galaxies and of their tails.

We can compare the properties of the tails to those observed in local galaxies. Unfortunately, at this redshift, the Hα line is outside the spectral domain of MUSE while Hβ is only barely detected (1.5-σ detection) in the tail of ID345 and undetected in ID473, we thus have to derive the intensity of the [O III] line and convert it into Hα assuming a standard [O III]/Hα ratio. Spectroscopic observations of the tails of ionised gas in ram pressure stripped galaxies of the local Universe are limited to the spectral domain $\lambda \geq 4000-9000$ Å (Yoshida et al. 2004, 2012; Fossati et al. 2016; Poggianti et al. 2017), preventing any estimate of this ratio from local measurement. The only direct measurement of the [O III]/Hα ratio in the stripped material of local galaxies is the value derived by Cortese et al. (2006) around some gravitationally perturbed galaxies in the cluster A1367 ([O III]/Hα = 2). We do not expect that the physical properties of the stripped gas, which is not associated to any stellar component and is probably embedded in a similarly hot and dense ICM, differ significantly from those observed in A1367. This value is consistent with the value derived using the 1.5-σ detection of Hβ in the tail of ID345 ([O III]/Hβ = 14.6) and the 3-σ upper limit in ID473 ([O III]/Hβ ≥ 4.6) and adopting Hα/Hβ = 2.86 if we make the reasonable assumption that the dust attenuation is negligible. We thus derive the Hα luminosity assuming [O III]/Hα = 2 ($L(\text{Hα}) = 1.3 \times 10^{41} \text{ erg s}^{-1}$ for ID345 and $L(\text{Hα}) = 2.5 \times 10^{40} \text{ erg s}^{-1}$ for ID473) and the mean surface brightness of the tails ($\Sigma(\text{Hα}) = 1.5 \times 10^{-18} \text{ erg s}^{-1} \text{ arcsec}^{-2}$ for ID345 and $\Sigma(\text{Hα}) = 1.3 \times 10^{-18} \text{ erg s}^{-1} \text{ arcsec}^{-2}$ for ID473). These numbers, which are close to the detection limits of modern instrumentation, are comparable to those observed in the nearby Universe. Due to cosmological surface brightness dimming, however, when transformed to physical units both $H\alpha$ luminosities and surface brightnesses are a factor of $\sim 10$ higher than those measured in local systems.

We can also use the [O III]/[O I] = 1.3729/[O I] = 1.15 ± 0.06 measured on the integrated spectrum of the tail of ID345, the corresponding electron density is $n_e = 200 \text{ cm}^{-3}$. As mentioned in Sect. 3.1, however, this is a light-weighted mean, and is thus probably biased towards the brightest and highest density regions, unresolved in the MUSE data. Indeed, this gas density perfectly matches that observed in star forming regions of galaxies at $z = 0$ (Sanders et al. 2016). The typical line ratio measured pixel per pixel in the diffuse tail is rather $[\text{O III}]/[\text{O I}] = 1.3729/[\text{O I}] = 1.15$, corresponding to a gas density $n_e \leq 10 \text{ cm}^{-3}$ (Osterbrock & Ferland 2006). This upper limit is consistent with the gas density derived from the [S II] 6716/[S II] 6731 line ratio measured in the diffuse tails of local galaxies, or independently with geometrical considerations (e.g. Fossati et al. 2016; Boselli et al. 2016a). As in Boselli et al. (2016a) and Fossati et al. (2016), we can also estimate the typical recombination time of the ionised gas, for the stellar disc major axis, also indicates that the gas stripping is occurring edge-on. Figure 5 shows the spectra of the galaxies and of their tails.

$$
\tau_{\text{rec}} = \frac{1}{n_e \alpha_A \lambda}
$$

where $\alpha_A$ is the total recombination coefficient ($\alpha_A = 4.2 \times 10^{-13} \text{ cm}^{-3} \text{ s}^{-1}$, Osterbrock & Ferland 2006). For $n_e = 10 \text{ cm}^{-3}$, $\tau_{\text{rec}} \approx 10^4 \text{ yr}$, a very short time compared to the travel time of the tail ($\tau_{\text{travel}} = 10^8 \text{ yr}$).

This very short recombination time suggests that, as in local galaxies, a source of gas excitation within the tail must be present. In the lack of photoionisation, which requires the
presence of star forming regions within the tail, other ionising mechanisms can be thermal conduction, magneto hydrodynamics waves, and shocks (Fossati et al. 2016; Boselli et al. 2016a). The presence of shock-ionised gas is suggested by the high [O II]/[O III]λ5007 ratio observed in the tails ([O II]/[O III]λ5007 ≥ 7 and 4.5 in ID345 and ID473, respectively; Dopita & Sutherland 1995). Part of the stripped gas might still be in other phases such as cold H1 or hot gas emitting in X-rays, as indeed suggested by simulations (Tonnesen & Bryan 2010, 2012).

4.2. Kinematical properties

Figure 4 shows the velocity field and the velocity dispersion map of the ionised gas over the two perturbed galaxies and along the tails. The velocity field of both galaxies is very symmetric and the difference between the receding and approaching sides of both almost edge-on rotating (> 70°) discs is ∼ 300 km s⁻¹. In addition, the size of the two galaxies is quite similar, which suggests that they have a comparable dynamical mass (cf. Table 2). The velocity of the gas is fairly constant along the tails and is a bit higher than that of the associated galaxies, which means that the gas is decelerated in the tail, confirming its stripped gas origin. This difference is higher for the northern galaxy ID473 (ΔV ∼ 100 km s⁻¹). The low velocities (in blue) associated to a higher velocity dispersion in the southern tail are due to the overlap of the tail with a galaxy of the cluster with a lower velocity than the tail (cf. Fig. 3). The velocity dispersion of the gas is high in the southern galaxy ID345 (∼ 131 km s⁻¹) which seems to host an active galactic nucleus (based on broad lines and a high [O III]λ5007/Hz ratio around 3.5 on the integrated spectrum).
Fig. 5. The MUSE integrated spectra corrected for variations in the velocity field of galaxy ID473 (upper panel), of its tail (upper middle panel), of galaxy ID345 (lower middle panel), and of its tail (lower panel). The associated standard deviation, which is shifted below zero for clarity, is shown in grey. The main lines at the redshift of the sources are indicated with grey dotted vertical lines. An emission around 7500 Å associated to a background [O\textsc{ii}] emitter is observed in the spectra of ID473’s tail. Fluctuations in the spectra of tails are due to imperfect bright star continuum subtraction and to faint background sources.
is lower (∼ 75 km s⁻¹) in the northern galaxy ID473, while the velocity dispersion of the gas along both tails is fairly high (∼ 80 km s⁻¹). We recall, however, that this is a light-weighted estimate of the velocity dispersion of the gas within the tails. It is comparable to the median dispersion along tails (∼ 90 km s⁻¹) determined on the velocity dispersion map (see Fig. 5), but much more uncertain due to the low signal-to-noise. Similar velocity dispersions are observed within the tail of local galaxies (e.g. ESO 137-001, Fumagalli et al. 2014).

5. Discussion

The presence of long tails of ionised gas without any old stellar counterpart suggests that the two galaxies are now undergoing a ram pressure stripping episode. The derived density, mass, and recombination time of ionised gas stripped during the interaction, as well as the shape and size of the tail associated to the two galaxies ID345 and ID473, are very similar to those observed in the massive spiral NGC 4569 in the Virgo cluster or ESO 137-001 in the Norma (A3627) cluster. The conditions for gas stripping via ram pressure, \( \rho_{\text{ICM}} V^2 > 2 \pi G \Sigma_{\text{gas}} \Sigma_{\star} \) (Gunn & Gott 1972), where \( \Sigma_{\text{gas}} \) and \( \Sigma_{\star} \) are the density of gas and stars over the disc of the galaxy, can be compared to those encountered in these nearby counterparts. Indeed, the velocity dispersion of the cluster CGr32 (< \( V_{\text{cluster}} \)) is close to that of Virgo (< \( V_{\text{cluster}} \)) at 800 km s⁻¹ (Boselli et al. 2014b) and Norma (< \( V_{\text{cluster}} \)) at 925 km s⁻¹ (Sun et al. 2010), where ram pressure stripping is active.

We use the radial profile of the intracluster electron density, \( n_e \), derived from XMM-Newton data (see Sec. 3.2) to estimate \( n_e \) at the position of the two target galaxies (Fig. 6). The azimuthal mean density of the hot intracluster gas at the position of the two galaxies ID345 and ID473 is \( n_e = 1.7 \times 10^{-3} \) and \( n_e = 1.6 \times 10^{-3} \) cm⁻³, respectively. These densities are comparable to those encountered in similar clusters in the redshift range \( z = 0.7 \) to \( z = 0 \) (Giodini et al. 2013; McDonald et al. 2017).

These electron densities can also be compared to that measured in the Virgo cluster at a similar radial distance from the cluster core (\( n_e \approx 2 \times 10^{-3} \) cm⁻³ at 100 kpc, \( n_e \approx 10^{-3} \) cm⁻³ at 200 kpc), or at the distance of NGC 4569 (\( n_e = 2 \times 10^{-4} \) cm⁻³ at 500 kpc) as derived from Suzaku and Planck data by Simionescu et al. (2017). It can also be compared to that in the Norma cluster at the distance of ESO 137-001 (\( n_e \approx 10^{-3} \) cm⁻³ at 180 kpc, Sun et al. 2010). The conditions encountered by the galaxies ID345 and ID473 in the cluster CGr32, very similar to those observed in similar objects in the local Universe, are optimal for an efficient ram pressure stripping event. The gas column density over the disc of the two galaxies is probably higher than those present in ESO 137-001 and NGC 4569, while the stellar density is probably lower just because they are observed at much earlier epochs (\( z = 0.7 \)). In particular we recall that NGC 4569 is a bulge dominated Sa galaxy. The relative absolute line-of-sight velocity with respect to the mean velocity of the cluster are \( V_{\text{ID345}} < V_{\text{CGr32}} = −2.824 \) km s⁻¹ and \( V_{\text{ID473}} < V_{\text{CGr32}} = −1903 \) km s⁻¹. The projected extension of the ionised gas tails suggests that the galaxies are also moving on the plane of the sky, thus these values should be considered as lower limits. These numbers can also be compared to the relative line-of-sight velocity of NGC 4569 with respect to Virgo, \( V_{\text{NGC 4569}} < V_{\text{Virgo}} = 1176 \) km s⁻¹, ESO 137-001 with respect to Norma, \( V_{\text{ESO 137-001}} < V_{\text{Norma}} = 191 \) km s⁻¹, and UGC 6697 with respect to A1367, \( V_{\text{UGC 6697}} < V_{\text{A1367}} = 132 \) km s⁻¹. This simple comparison suggests that, as in their local counterparts, ID345 and ID473 are suffering a ram pressure stripping event. It is also worth mentioning that one of the two galaxies, ID345, shows prominent Balmer absorption lines (see Fig. 5), typical in objects suffering an abrupt variation of the star formation activity. Its position above the main sequence (at \( z = 0.7 \)) is close to the mean density of the hot intracluster gas at 100 kpc, or at the distance of NGC 4569, at 250 kpc, ESO 137-001 with respect to Norma, at 180 kpc, NGC 4569 with respect to Virgo, at 1176 km s⁻¹, and Norma R star indicate the position of the galaxies ID345, ID473 in CGr32, NGC 4569 and UGC 6697.

### Table 1: Tabulated data (simulated sample)

| Cluster | ID345 | ID473 | CGr32 |
|---------|-------|-------|-------|
| Mass    | 5.5   | 4.2   | 7.8   |
| Distance| 100   | 200   | 500   |
| Velocity| 80    | 100   | 50    |

The electron density of the ICM at the distance of NGC 4569 is significantly different than the one reported in Boselli et al. (2016b) which was based on old ROSAT data.
they come from a different region of the COSMOS Wall, which seems extended several Mpc along the line-of-sight (Lovino et al. 2016).

If the gas keeps the dynamical imprint of the region from where it has been stripped and is decelerated by the interaction with the hot ICM, as indeed observed in local edge-on galaxy UGC 6697 in A1367 (Consolandi et al. 2017). Fig. 3 can be interpreted as follows: in the northern galaxy ID473 the gas is decelerated in the tail with respect to the galaxy, which means that the trajectory of the galaxy within the cluster is not on the plane of the sky but it is rather on the line of sight, thus the galaxy is crossing the cluster from the background. This could explain why the tail is relatively short compared to that of ID345. Indeed, in the southern galaxy ID345, the less pronounced velocity offset between the galaxy and the tail, and the extension of the tail, suggest that the trajectory of the galaxy within the cluster is mainly on the plane of the sky. The observed large velocities along the tail may be due to a combination of gas in the tail being decelerated and gas being stripped from the receding side of the galaxy. The two galaxies show a relatively high velocity dispersion of the gas both in their discs and in the tails (∼ 100 km s⁻¹). Given their almost edge-on trajectories, this could result from the contribution of the gas stripped from both the approaching and receding sides of the rotating disc, whose contribution cannot be resolved because of beam smearing, as indeed observed in the edge-on galaxy UGC 6697 in A1367 (Consolandi et al. 2017).

We notice, however, that the velocity dispersion of the gas in the tail is smaller than the maximum rotational difference between the two sides of both galaxies (∼ 150-200 km s⁻¹). To conclude, ID345 has probably already passed pericentre, while ID473 is a fresh infaller as suggested by its position in the phase-space diagram. Galaxies with properties similar to ID345 (eccentric position in the phase-space and tails oriented toward the cluster centre), although unusual, are also present in local clusters (e.g. NGC 4569, Boselli et al. 2014b 2016a).

We can also compare the properties of the two galaxies to the most recent results from cosmological hydrodynamic simulations, and in particular to the predictions of IllustrisTNG (Yun et al. 2019) which are perfectly tuned for a comparison with our targets. In done for galaxies (M star ≳ 10¹² M⊙) and clusters (10¹³ M⊙ ≲ M gas ≲ 10¹⁶ M⊙) of similar mass. These simulations indicate that galaxies with tails of stripped gas due to ram pressure stripping are frequent in clusters with a redshift z ≲ 0.6. About 30% of the disc galaxies have such a cometary shape in the gaseous component with a very weak dependence on redshift. They also show that these objects are more frequent at intermediate to large clustercentric radii (r/R₂₀₀ ≳ 0.25), that for the cluster CGr32 corresponds to ∼ 250-400 kpc), in galaxies with a high velocity with respect to the mean velocity of the cluster, and in more massive clusters. The simulations also show that the orientation of the tail, which generally traces the trajectory of the galaxy within the high-density region, does not depend on the relative position of the galaxy with respect to the cluster centre. We recall that ID345 and ID473 are located at ∼ 200 kpc in projection from the cluster core, have the tails oriented almost towards the cluster centre, and have a high velocity along the line of sight with respect to that of the cluster, and thus match all the properties of perturbed galaxies in the simulations.

6. Conclusion

As part of the MUSE-gALaXY Groups In Cosmos (MAGIC) GTO program we observed the cluster of galaxies CGr32 (M₂₀₀ ≳ 2 × 10¹⁵ M⊙) at z=0.73. The MUSE observations reveal the presence of two massive (Mgas ≳ 10¹⁰ M⊙) galaxies with extended low-surface brightness tails of diffuse gas detected in the [O ii] emission-line doublet. The cometary shape of the tails and the lack of any diffuse stellar counterpart in the very deep Subaru images clearly indicate that the two galaxies are undergoing a ram-pressure stripping event. This result is thus the first evidence that the dynamical interaction between the cold galaxy ISM with the hot and dense ICM, which is probably the dominant perturbing mechanism in high density environments in the local Universe, was also active at earlier epochs, when the Universe had only half of its present age. This result is consistent with the predictions of the most recent cosmological simulations of galaxy evolution.

The density of the gas within the tail derived using the [O ii]λ3729/[O ii]λ3726 line ratio indicates that the recombination time, tREC ≳ 10⁴ yr, is very short compared to the travel time of the tail, ttravel ≳ 10⁵ yr, as often observed in local galaxies. This suggests that a source of gas excitation must be present within the tail. To conclude, this work is a further confirmation that the extraordinary IFU capabilities of MUSE in terms of field of view and sensitivity can be successfully used to extend local studies to the high redshift Universe, thus opening a new era in the study of the role of the environment on galaxy evolution.

Acknowledgements. We thank the anonymous referee for constructive comments and suggestions. This work was supported by the Programme National Cosmology et Galaxies (PNCG) of CNRS/INSU with INP and IN2P3, co-funded by CEA and CNES. This work has been carried out thanks to the support of the ANR FOGHAR (ANR-13-BS05-0010-02), the OCEVU Labex (ANR-11-LABX-0060) and the A*MIDEX project (ANR-11-IDEEX-0001-002) funded by the “Investissements d’Avenir” French government program managed by the ANR. VA acknowledges the COLCIENCIAS (Colombia) PhD fellowship program No. 756-2016. JB acknowledges support by FCT/MCTES through national funds by grant UID/FIS/04434/2019 and through Investigator FCT Contract No. IF/01654/2014/CP/215/CT0003. This work made use of observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

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5 Since these simulations do not discriminate between the different gas phases, it is not astonishing that the fraction of galaxies with observed tails in the ionised gas is significantly lower than 30%.
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