



Chapter 3:
The Decline of Star Formation:
Feedback, Fuel shortage or Inefficiency?

The spatially resolved view of star formation in galaxy clusters

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Abstract. Integral field spectroscopic studies of galaxies in dense environments, such as clusters and groups of galaxies, have provided new insights for understanding how star formation proceeds, and quenches. I present the spatially resolved view of the star formation activity and its link with the multiphase gas in cluster galaxies based on MUSE and multi-wavelength data of the GASP survey. I discuss the link among the different scales (i.e. the link between the spatially resolved and the global star formation rate-stellar mass relation), the spatially resolved signatures and the quenching histories of jellyfish (progenitors) and post-starburst (descendants) galaxies in clusters. Finally, I discuss the multi-wavelength view of star-forming clumps both in galaxy disks and in the tails of stripped gas.

Keywords. Galaxy evolution; star formation; baryonic cycle; galaxy clusters

1. Introduction

When galaxies infall into clusters and move at high speed with respect to the hot intracluster medium (ICM), the ram pressure (RP) exerted by the ICM upon the galaxy interstellar medium (ISM) can remove the galaxy gas, wherever the RP exceeds the gravitation pull (Gunn & Gott 1972, Jaffe' et al. 2018). The hot halo gas is affected first, then the disk gas is removed starting from the outer disk regions and stripping works its way inward in the disk, until the galaxy remains eventually devoid of gas.

Neutral gas studies were the first direct evidence for gas stripping in clusters, revealing HI tails, truncated HI disks, HI disturbed morphologies and a progressively increasing HI deficiency towards the central regions of clusters (see Cortese et al. 2021 for a recent review). By now, observations of extraplanar tails of stripped material have been obtained with several different methods (HI line, integral-field spectroscopy, H α imaging, X-ray emission, radio continuum, UV and optical imaging, see Boselli et al. 2022), showing tails of gas in different phases and even tails of stars formed in the stripped gas. It is important to realize that each of the methods for identifying galaxies affected by ram pressure provides only a partial view of this phenomenon.

The GASP (GAs Stripping Phenomena in galaxies) project investigates the physical mechanisms that remove gas from galaxies and their effects on the star formation activity and galaxy structure. This programme has been studying galaxies in low redshift clusters, groups, filaments and isolated galaxies, but in these proceedings I will focus on cluster galaxies only. Readers are referred to Vulcani et al. (2021) for an overview of non-cluster galaxies.

GASP provides the only large sample of confirmed ram-pressure stripped galaxies with integral-field (IF) spectroscopy. It consists of 64 ram-pressure stripped galaxies with a wide range of stellar masses (10^9 - $10^{11.5} M_{\odot}$), that were selected for showing unilateral

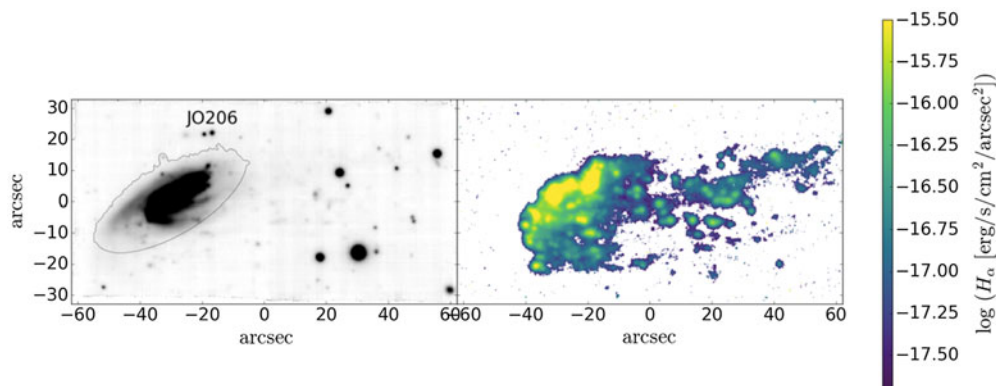


Figure 1. The jellyfish galaxy JO206, a massive ($9 \times 10^{10} M_{\odot}$) galaxy in a low mass cluster (velocity dispersion $\sim 500 \text{ km s}^{-1}$). Left. White-light MUSE image. Right. MUSE map of $H\alpha$ emission. Note the tentacles of stripped ionized gas departing for ~ 80 kpc from the disk, to the west. Clearly visible in this tail are $H\alpha$ -emitting, star-forming clumps. From Poggianti et al. (2017a).

debris in B-band images. They are hosted in 39 low redshift clusters ($z = 0.04\text{--}0.07$) whose velocity dispersions range from ~ 500 to $\sim 1400 \text{ km s}^{-1}$.[†] These galaxies have various stages and degrees of stripping, from weak or initial signs of stripping, to very strong stripping (“jellyfish galaxies”, with long gas tails, Fig. 1), to the final stages of stripping (truncated disks with gas only left in the galaxy center). Their properties can be contrasted with the GASP control sample of 30 undisturbed galaxies. Recently, MUSE data of distant galaxy clusters have started to allow the first detailed studies of ram-pressure ionized gas tails also at higher redshifts (2 galaxies at $z = 0.7$, Boselli et al. 2019; 13 galaxies at $z = 0.3\text{--}0.4$, Moretti et al. 2022, Bellhouse et al. 2022).

The GASP survey is based on a MUSE ESO Large Program (spatial resolution $\sim 1 \text{ kpc}$, galaxy coverage out to 7 effective radii on average), complemented by multi-wavelength follow-up programs with ALMA, APEX, JVLA, MeerKAT, ATCA, UVIT@ASTROSAT, LOFAR and Chandra. Thus, the GASP multi-wavelength coverage allows us to investigate all the main processes related to star formation, including gas in different phases, the stellar content and non-thermal processes.

2. Global and spatially resolved star formation rate-mass relation in the disks of galaxies

The existence of a relation between the integrated star formation rate (SFR) and the total stellar mass of galaxies (hereafter, “global” SFR-M relation) has been known for many years and has been observed from $z = 0$ to beyond $z = 2$. A correlation between the stellar mass surface density and the SFR surface density has been found in all integral-field spectroscopy surveys, even at higher redshifts, suggesting that the global relation originates from a perhaps more fundamental relation on small (1kpc) scales (Wuyts et al. 2013, Sanchez et al. 2013). The scatter in this relation is related to Hubble type (Gonzalez-Delgado et al. 2016) and variations in star formation efficiency (Ellison et al. 2020). Reaching larger galactocentric radii than any other large IF survey, GASP has shown that the resolved SFR-M correlation of undisturbed galaxies is broad, and that the scatter mainly arises from bright off-center star-forming knots. Moreover, each galaxy has a distinct resolved relation and the global relation appears to be driven by the existence of the size-mass relation (Vulcani et al. 2019).

[†] Cases of GASP ram-pressure stripped galaxies in groups and even in filaments have been presented in Vulcani et al. (2021) and references therein.

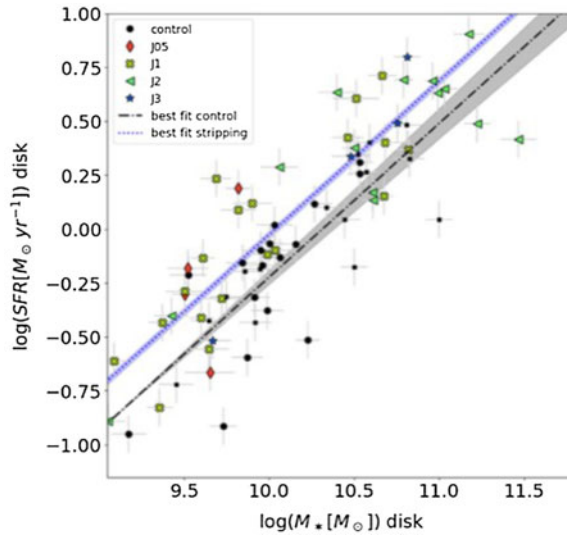


Figure 2. Global SFR–M relation for undisturbed galaxies (black points, grey line fit) versus RP stripped galaxies (colored points, light blue line fit). RP galaxies show a modest but significant enhancement in their SF activity. From [Vulcani et al. \(2018\)](#)

Ram-pressure stripped galaxies show a moderate enhancement of SFR in the disk for their stellar mass, lying on average above the global SFR–M relation of undisturbed galaxies by 0.2 dex (Fig. 2, [Vulcani et al. 2018](#), [Roberts & Parker 2020](#)). Thus, during the initial and strongest stages of stripping, ram pressure enhances SF before leading to quenching. On spatially resolved scales, we find again an enhancement of SFR density at a given mass density at all galactocentric distances, consistent with being induced by RP compression waves ([Vulcani et al. 2020b](#)).

3. From stripping to quenching: post-starburst galaxies and AGN

RP stripping of the disk, and consequent quenching, proceeds mostly outside-in, or side-to-side if the galaxy is plunging edge-on into the ICM. It is therefore common to observe RP stripped galaxies still with ionized gas and intense star formation in their central regions as well as long tails of ionized gas, but having their outer disk regions already devoid of ionized gas and recently quenched ([Gullieuszik et al. 2017](#), [Poggianti et al. 2017a, 2019b](#), [Bellhouse et al. 2017, 2019](#); [Werle et al. 2022](#)). These outer regions present typical post-starburst (PSB) spectra ([Dressler & Gunn 1982](#), [Poggianti et al. 1999](#)), with no emission lines and strong Balmer lines in absorption, indicative of a local sudden truncation of the star formation activity at some point during the past ~ 0.5 Gyr. It has been suggested that the strong decline of star formation is responsible for the global radio continuum excess of RP stripped galaxies compared to their ongoing SFR seen by LOFAR ([Ignesti et al. 2022a,b](#)), and that the high radio-to- $H\alpha$ ratio in tails compared to disks is due to relativistic electrons advected from the disks.

If gas is totally stripped, the end product of this evolution is a PSB galaxy, with no ionized gas and no SF left anywhere in the disk. The GASP samples, both at low- z and in distant clusters, include by construction several PSB galaxies whose quenching history can be studied in details applying spectrophotometric codes ([Fritz et al. 2017](#)) to the MUSE spectroscopic datacube ([Vulcani et al. 2020a](#), [Werle et al. 2022](#)). The stellar history maps confirm indeed mostly outside-in and side-to-side quenching, with characteristic signatures indicating that most cluster PSBs originate from RP stripping ([Vulcani et al. 2020a](#), [Werle et al. 2022](#)). The MUSE spectra also reveal that generally,

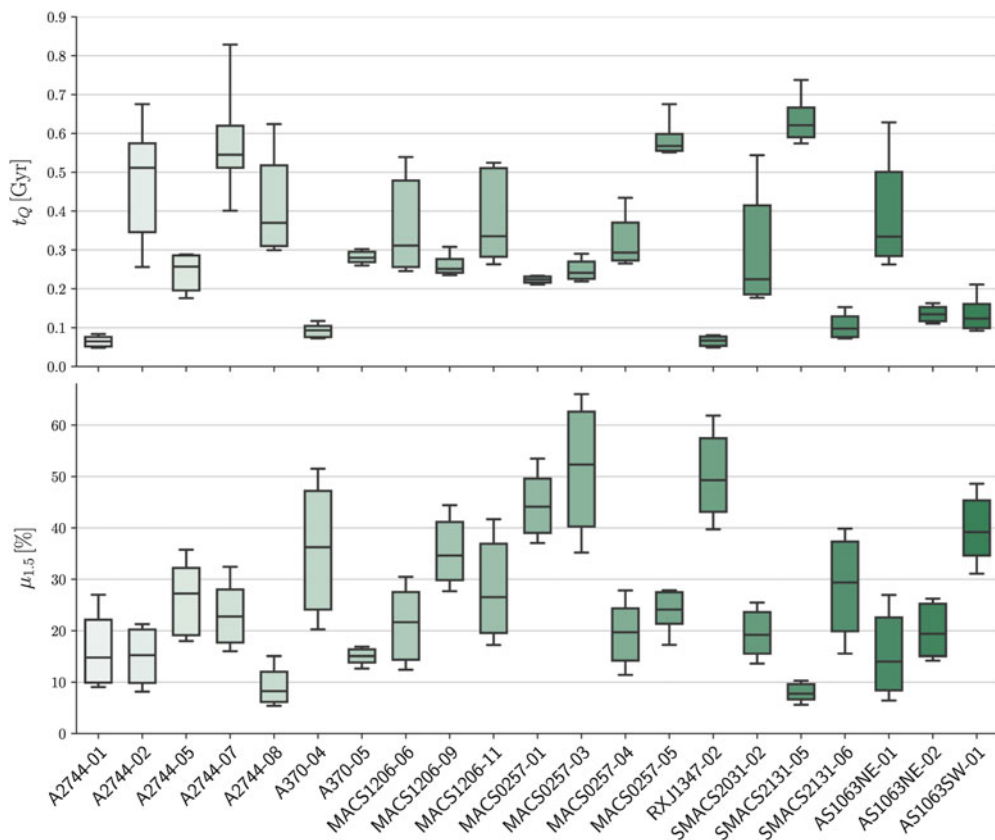


Figure 3. Characteristics of a sample of PSB galaxies in $z = 0.3\text{--}0.4$ clusters. Top. Time since quenching. Bottom. Fraction of mass assembled during the last 1.5 Gyr, used to roughly estimate the mass fraction involved in the burst prior to truncation. Boxes represent the 25th and 75th percentiles, the median is the horizontal line and the whiskers are the 15th and 85th percentiles. From Werle et al. (2022).

a strong local starburst takes place before the SF truncation, accounting for significant fractions of the mass formed (Fig. 3). Moreover, the quenching timescales and the total time it takes to quench all spaxels can be derived (Werle et al. 2022).

Interestingly, a small fraction of the PSB galaxies in distant clusters present an inside-out quenching, associated with AGN episodes which are still detectable from the MUSE emission lines in the centers (Werle et al. 2022). The quenching history in these cases appears to be dominated by AGN feedback, though this may be indirectly induced by RP. In fact, an usually high incidence of AGN has been found among strongly RP stripped galaxies (Poggianti et al. 2017), leading in some cases to AGN driven outflows of ionized gas (Radovich et al. 2019) and strong AGN feedback sweeping a large region around the galaxy center (George et al. 2019).

Recently, based on a combination of GASP galaxies and all available literature data for RP stripped galaxies, contrasted with a MANGA mass-matched undisturbed sample, Peluso et al. (2022) has confirmed that the incidence of AGN is higher in RP stripped galaxies. This phenomenon seems to occur preferably during the strongest phase of stripping, when the gas tails are longest. Hydrodynamical simulations reach similar conclusions (Ricarte et al. 2020; Farber et al. 2022). Simulations have previously shown

that loss of angular momentum due to the interaction of the rotating ISM with the non-rotating ICM can potentially draw gas on lower orbits, and recent work has clarified the respective roles of mixing and torques from pressure gradients (Akerman et al. 2023 submitted).

4. Star formation in the tails of stripped gas and gas mixing with the intracluster medium

The fact that new stars can form in-situ in the stripped gas, outside of the galaxy disk and even far out in the stripped tails, has been shown by many studies using several different SF indicators (e.g. Yagi et al. 2007; Smith et al. 2010; Sun et al. 2010; Merluzzi et al. 2013; Fumagalli et al. 2014; Fossati et al. 2016; Consolandi et al. 2017; Boselli et al. 2018; Abramson et al. 2011; Kenney et al. 2014; George et al. 2018; Cramer et al. 2019).

In the extraplanar H α emitting tails of GASP stripped galaxies the dominant ionization mechanism is indeed photoionization by young massive stars, as obtained by MUSE BPT diagrams (Poggianti et al. 2019a). This SF takes place in H α -bright, dynamically cold star-forming clumps formed in-situ in the tails with luminosities similar to giant and super-giant HII regions (Fig. 1, Poggianti et al. 2019a).

The star formation occurring in the tail can produce from a negligible fraction to up to $\sim 20\%$ of the total SFR of the system (disk+tail) (Poggianti et al. 2019a), and the fraction of star formation in the tails roughly follows the fraction of gas that is stripped according to traditional analytical formulation (Gullieuszik et al. 2020): the SFR in the tail can thus be roughly predicted, in a statistical sense, knowing four main observable quantities: galaxy mass, cluster mass, galaxy line-of-sight velocity within the cluster and projected clustercentric distance.

With HST, using broad band filters spanning from UV to I-band and a narrow-band filter covering H α , we can now study at higher spatial resolution (70pc) the star-forming clumps, in the disks, in the vicinity of the disk but “extraplanar”, and in the tails. For a large sample of both H α -selected (over 2400 clumps) and UV-selected (over 3700) clumps in GASP jellyfish galaxies we have been able to study sizes, luminosities, hierarchical structure as well as stellar masses, star formation histories and stellar ages (Giunchi et al. submitted, Werle et al. in prep.). H α and UV luminosity and size distribution functions, together with luminosities-size relations, can be found in Giunchi et al. (2023, submitted).

The emerging picture is that basic star-forming clump properties such as luminosity and size do not depend strongly on whether the clumps are sitting in a galaxy disk or far out in the tail without an underlying disk. These characteristics of GASP clumps resemble more closely those in highly turbulent, H α -bright galaxies (Fisher et al. 2017) than those in normal low- z spiral galaxies (see Giunchi et al. 2023 for details).

Interestingly, H α and UV-selected clumps can be embedded in larger star-forming complexes emitting at optical wavelengths (V -band), whose total masses range typically from 10^4 to $10^7 M_{\odot}$ (Werle et al. in prep.). Thanks to these data, it is now possible to investigate the fate of these clumps, whether they are likely to remain intracluster isolated entities (Globular clusters? Ultracompact dwarf galaxies? Ultradiffuse galaxies?), or get dispersed and go to contribute to the general intracluster light.

Stripped material and intracluster material can exchange baryons in both directions. Evidence for mixing between the stripped interstellar medium (ISM) and the intracluster medium (ICM) has accumulated over the past few years, based e.g. on X-ray (Poggianti et al. 2019b, Campitiello et al. 2021, Sun et al. 2022; Bartolini et al. 2022) and on the analysis of the diffuse ionized gas (Tomicic et al. 2021a,b). The most direct evidence for ICM-ISM mixing has come from the gas metallicity in the stripped gas, which decreases along the tails, going away from the disk (Fig. 4, Franchetto et al. 2021, as predicted also in hydrodynamical simulations (Tonnesen & Bryan 2021).

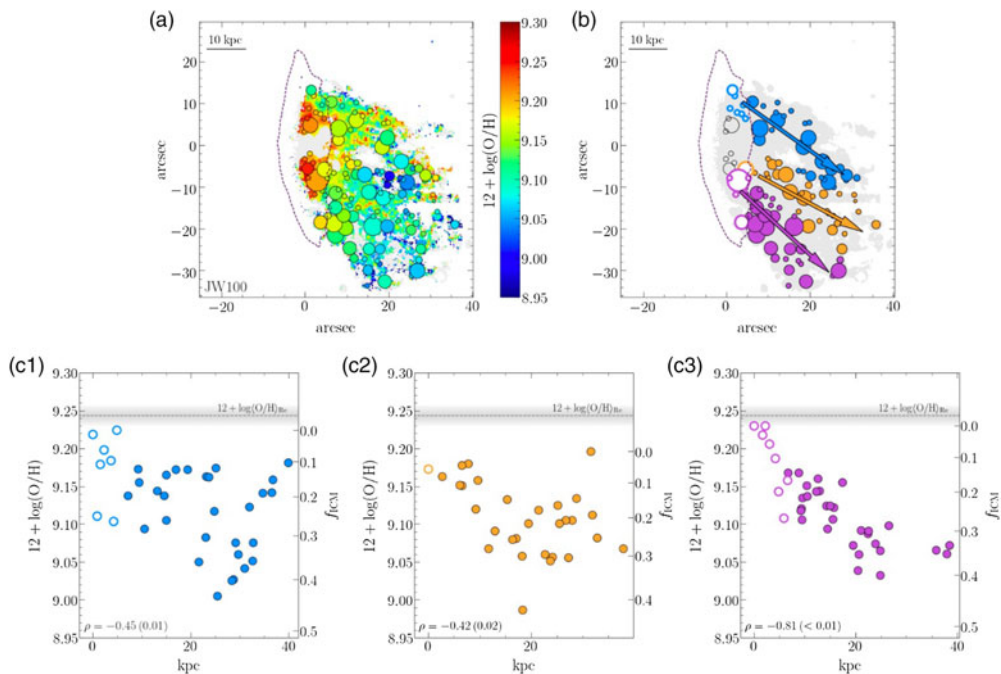


Figure 4. MUSE gas metallicity map of the galaxy JW100 (top left). Three main tails can be identified (top right). The metallicity strongly decreases along each tail (bottom panels). Assuming a typical ICM metallicity of 0.3 times solar, the fraction of gas provided by ICM mixing can be estimated (right Y-axes in bottom panels). From (Franchetto et al. 2021).

Overall, the data supports a scenario in which the stripped gas gets mixed with the ICM, accreting a significant fraction of mass, and still manages to cool and collapse to form new stars. Observations of the magnetic field aligned with the tail in the stripping direction in the JO206 GASP jellyfish galaxy favor a “magnetic draping” scenario (the galaxy moving within the magnetized ICM sweeping up the surrounding magnetic field, Dursi & Pfrommer 2008) and point out that the magnetic field may play a role favoring the SF in the tails by reducing the thermal conduction between ICM and ISM, hence the ISM evaporation (Mueller et al. 2021).

In order to complete the picture, there is another crucial stage in the star formation process: the molecular cloud formation from the neutral gas, as discussed below.

5. Neutral gas, molecular gas and star formation

As mentioned above, no selection method can provide the whole census of ram pressure stripped galaxies. It is thus of fundamental importance to obtain multi-wavelength information for samples selected in different ways. Only then we will be able to understand under what conditions multiphase tails are formed, and what is the evolutionary sequence among the observations of tails seen at different wavelengths. There are still relatively few RPS galaxies for which a detailed multi-lambda coverage is available (e.g. ESO137-001 and JW100).

For a subset of the GASP jellyfish galaxies, both HI and CO observations have been collected, in addition to MUSE. These GASP jellyfish galaxies are slightly HI deficient compared to similar non-stripped galaxies but have a significant excess of star formation for their HI content (Fig. 5, Ramatsoku et al. 2019, 2020; Deb et al. 2020, 2022, see also Luber et al. 2022 for an HI comparison of jellyfish and other cluster galaxies).

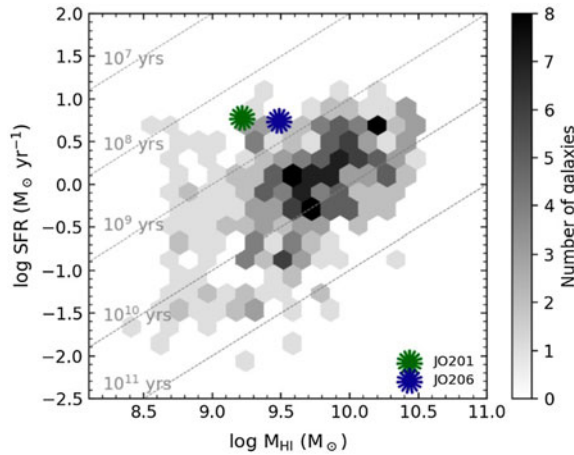


Figure 5. Global SFR - HI mass relation for two GASP jellyfish galaxies (JO201 and JO206), compared to a sample of normal spirals of similar masses (grey distribution). In jellyfish galaxies there is a clear excess of SF for their HI mass. From Ramatsoku et al. (2020), see also Deb et al. (2022).

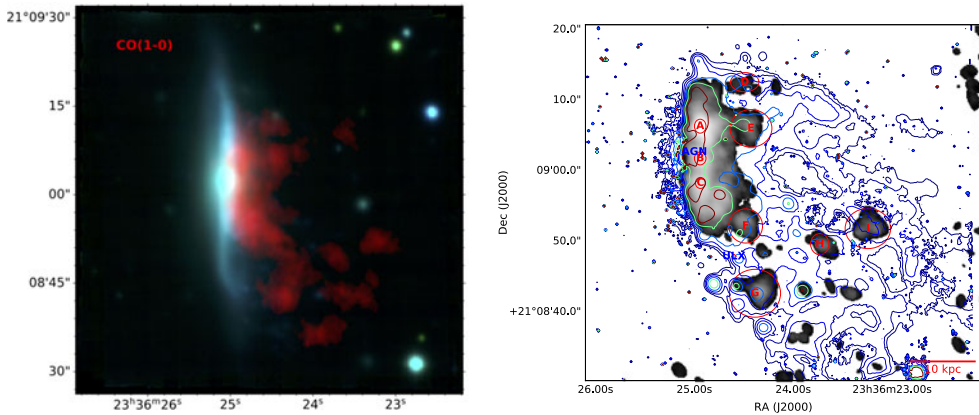


Figure 6. ALMA molecular gas (CO(1-0) emission in the jellyfish galaxy JW100 (red in the left panel, grey in the right panel). Left. There is a large amount of extraplanar CO, in clouds with molecular gas masses ranging from 10^6 to $10^9 M_{\odot}$. Right. Blue contours are the $H\alpha$ emission. While molecular gas close to the disk may be partly stripped, the clouds far out in the tail must have formed in-situ. From Moretti et al. (2020b).

These same galaxies have very large amounts of molecular gas, as estimated from their CO(2-1) and CO(1-0) emission (Fig. 6, Jachym et al. 2017, 2019; Moretti et al. 2018b, 2020a,b). Their molecular gas mass at a given stellar mass is 4-5 times higher than in undisturbed galaxies (Fig. 7). The molecular to neutral gas ratio in their disks is between 4 and 100 times higher than normal. Surprisingly, overall, the total (molecular plus neutral) gas mass is similar to that in normal galaxies. These results, shown in Moretti et al. 2020b, are solid irrespective of the conversion factors used for CO to H_2 and they suggest a very efficient conversion of neutral gas into molecular gas in jellyfish galaxies.

As far as the star formation efficiency is concerned (ratio between star formation rate and molecular gas mass) this appears to be significantly lower in the tails than in normal spirals, with long depletion times up to 10^{10} yr (Moretti et al. 2020b, and in prep.).

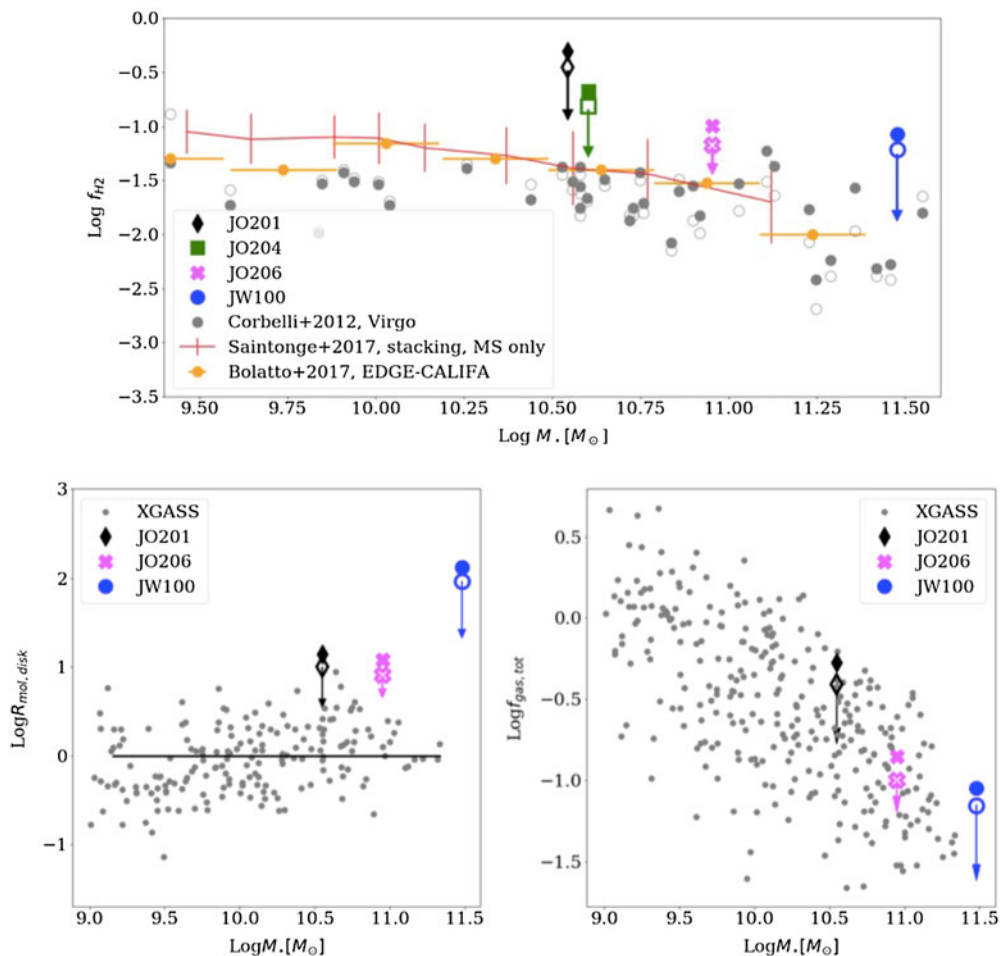


Figure 7. The molecular gas content of 4 GASP jellyfish galaxies obtained with ALMA (colored symbols) is compared with samples of normal galaxies (grey points and lines). Top. Ratio of molecular gas mass and galaxy stellar mass as a function of stellar mass. Bottom left. Molecular to neutral gas mass ratio versus stellar mass. Bottom right. Total (molecular+neutral) gas mass over stellar mass as a function of stellar mass. From [Moretti et al. \(2020b\)](#).

MeerKAT is soon to provide HI-selected samples for which additional multi-wavelength informations, including molecular gas estimates, have been secured.

6. Conclusions

Ram-pressure stripped galaxies are unique laboratories to study the star formation process and the baryonic cycle under unusual conditions. Gas clouds in stripped tails are embedded within the hot ICM and do not experience the influence of an underlying stellar disk, yet stars are commonly formed in stripped tails of multi-phase gas. Also in the galaxy disks, SF appears to be slightly enhanced globally, and strongly enhanced locally at any given time, where gas is still left. We witness an exceptionally efficient conversion of neutral to molecular gas in these galaxies, while the star formation efficiency ranges from usually normal in disks to much lower than normal in tails. PSB galaxies are the natural end-product of the stripping and subsequent quenching, and AGN activity possibly triggered by RP itself sometimes contributes in an inside-out manner to the quenching. I have presented only some of the highlights of the GASP project concerning

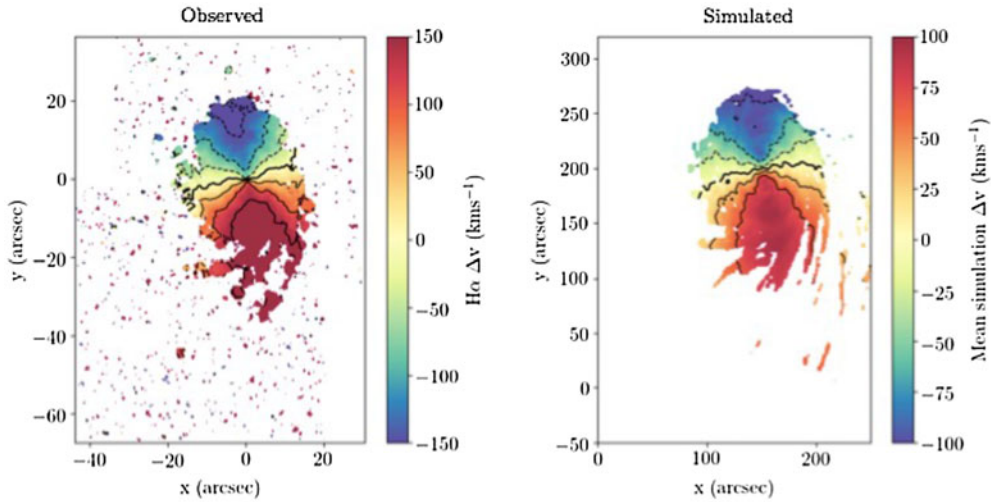


Figure 8. Example of unwinding arms in a RP stripped galaxy (JO200). The observed $H\alpha$ velocity map (left) is compared with RP simulations (right). From Bellhouse et al. (2021).

the star formation activity and the baryonic cycle in cluster galaxies. I have not presented the consequences of the RP-induced SF on the galaxy structure: as an example, RP stripping can cause the unwinding of spiral arms without the contribution of tidal interactions (Fig. 8, Bellhouse et al. 2021). Interested readers can find the full list of GASP publications at <https://web.oapd.inaf.it/gasp/>.

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