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The role of environment on quenching, star formation and AGN activity

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Abstract. Galaxies undergoing ram pressure stripping in clusters are an excellent opportunity to study the effects of environment on both the AGN and the star formation activity. We report here on the most recent results from the GASP survey. We discuss the AGN-ram pressure stripping connection and some evidence for AGN feedback in stripped galaxies. We then focus on the star formation activity, both in the disks and the tails of these galaxies, and conclude drawing a picture of the relation between multi-phase gas and star formation.

Keywords. Galaxies: active, galaxies: evolution, galaxies: clusters: general

1. Introduction

Spiral galaxies in clusters and groups lose their gas due to the ram pressure exerted by the hot intergalactic medium on the galaxy interstellar and circumgalactic medium. The effects of ram pressure stripping (RPS) on the disk gas have been observed at several different wavelengths (e.g. Gavazzi 1989; Kenney *et al.* 2004; Yagi *et al.* 2010; Sun *et al.* 2010; Smith *et al.* 2010; Ebeling *et al.* 2014; Gavazzi *et al.* 2018; Boselli *et al.* 2020) and have been predicted by both analytical approaches and hydrodynamical simulations (Gunn & Gott 1972; Tonnesen & Bryan 2009; Roediger & Brüggen 2008; Roediger *et al.* 2014). Stripped galaxies offer a great opportunity to study several fundamental physical processes in astrophysics, especially thanks to recent integral-field spectroscopic studies.

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† http://web.oapd.inaf.it/gasp/index.html

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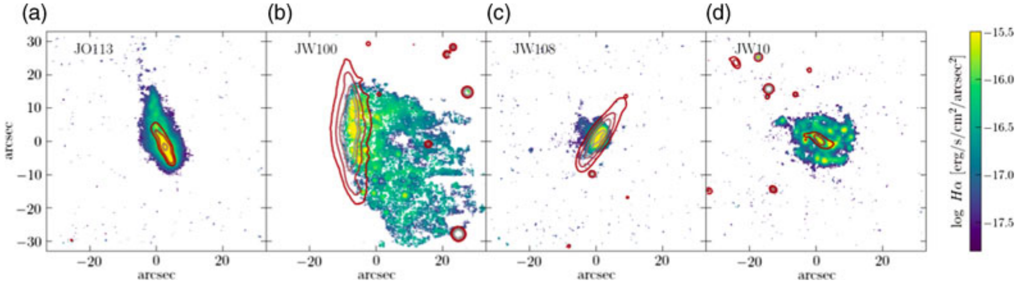

Figure 1. MUSE Hα surface brightness maps for four GASP galaxies in different conditions of RPS: a galaxy undergoing moderate stripping (JO113); a jellyfish galaxy (JW100); an advanced stage of stripping, with gas left only in the central region of the disk (JW108) and a galaxy that is disturbed but not stripped (JW10): the latter is a merger, as testified by the stellar velocity map (not shown). Red contours delimit the galaxy stellar disk. From Jaffé *et al.* 2018.

Hereafter, we will discuss the latest results of ram pressure studies concerning three fields of research: the triggering of AGN activity; the star formation process within and outside of galaxy disks; and the baryonic cycle between multi-phase gas and star formation. As we discuss below, unexpected findings were uncovered for each of these fields.

Our summary is mostly based on results from the survey GASP (GAs Stripping Phenomena in galaxies, Poggianti *et al.* 2017a, http://web.oapd.inaf.it/gasp/index.html), which includes a MUSE integral-field ESO Large Program and follow-up multiwavelength programs investigating the molecular gas (APEX, ALMA), the neutral gas (JVLA, MeerKAT) and the young stellar content (UVIT@ASTROSAT). The GASP sample includes cluster galaxies at different stages and different strengths of the stripping process (Fig. 1), from initial to peak stripping to the late phases with little gas left, and even fully stripped post-starburst galaxies and an undisturbed control sample. GASP also includes a group and field subsample of galaxies, which are not discussed here (Vulcani *et al.* 2017, 2018a,c, 2019a,b).

2. AGN

An unexpected result was the high incidence of AGN among the so called “jellyfish galaxies”, defined as galaxies with one-sided tails of ionized gas (longer than the stellar disk diameter). MUSE data demonstrate that the tails are due to RPS. Six out of the seven GASP jellyfish galaxies studied hosted an AGN (one of them is an optical LINER). This AGN incidence is much higher than in general cluster and field samples, suggesting that ram pressure can cause gas to flow towards the center and trigger the AGN activity (Poggianti *et al.* 2017b, Fig. 2).

The exact physical mechanism responsible for the gas inflow still needs to be pinpointed. It may be due to a loss of angular momentum of the galactic gas when it interacts with the non-rotating intracluster-medium (Tonnesen & Bryan 2012), or it can be generated by oblique shocks in a disk flared by the magnetic field (Ramos-Martínez, Gómez & Pérez-Villegas 2018). Very recent high resolution simulations of a galaxy cluster also find that ram pressure triggers enhanced accretion onto the central black hole (Ricarte *et al.* 2020).

In this context, it is relevant to ask: a) how sure is the presence of the AGN, and could the gas ionization be due to shocks or other mechanisms? Based on the comparison with AGN, shocks and HII-region photoionization models and using different line ratios, Radovich *et al.* (2019) confirmed the univocal interpretation of the presence of AGN. The same work found iron coronal lines (Fig. 2) and extended (>10kpc)

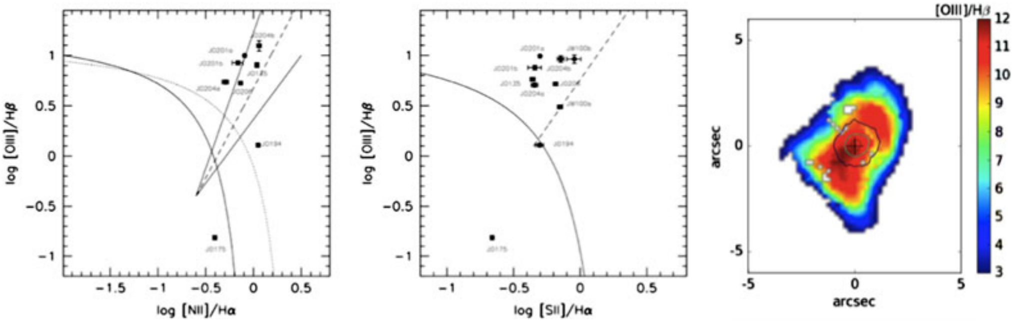

Figure 2. Left and center. BPT line-ratio diagnostic diagrams for the jellyfish sample from Poggianti *et al.* (2017b). Most galaxies lie in the AGN region of this diagram. Right: The high [OIII]/Hβ ratio of the central region of the JO201 jellyfish galaxy indicates the presence of the AGN. The black contour shows the region with emission of the coronal [Fe VII]λ6087 line, also indicative of an AGN. From Radovich *et al.* (2019).

AGN-powered ionization cones in some of these galaxies, as well as AGN outflows extending out to 1.5-2.5 kpc from the center, with outflow velocities in the range 250-550km s^{-1}. b) The sample published in Poggianti *et al.* (2017b) is small, and consists of quite massive galaxies ($\geqslant 4 \times 10^{10} M_\odot$). How significant is the enhancement of the AGN fraction, and is that confirmed by further studies? Is the RPS-enhanced AGN activity present only under certain circumstances, e.g. in a certain stage of stripping (when it is strongest), or for certain orbits within the cluster, etc? Or does it occur only in galaxy clusters with certain intracluster medium properties? For example, Roman-Oliveira *et al.* (2019), in their study of the A901/2 supercluster, find only 5 AGN host galaxies in their sample of 58 jellyfish candidates with an assigned classification (see also Roman-Oliveira in these proceedings). The analysis of the whole GASP sample is underway, and studies of other samples/redshifts will help clarify this point, keeping in mind that the detection of a Seyfert2/LINER AGN depends crucially on the data quality and sensitivity. Furthermore, for several galaxies there is evidence for a large amount of dust in their nuclear regions: in this case, the optical line diagnostic ratios provided even by deep MUSE data sometimes may not reveal the dust obscured AGN (e.g. Fritz *et al.* 2017), and X-ray data would be required for its detection.

Moreover, the combination of MUSE and multiwavelength data has provided strong evidence for the effects of AGN feedback in the jellyfish galaxy JO201 (George *et al.* 2019, see also Bellhouse *et al.* 2017, 2019). The central 8kpc region of JO201 is depleted of both molecular gas (as traced by a CO ALMA observation) and of recent and ongoing star formation (as traced by NUV and FUV imaging with UVIT@ASTROSAT) (Fig. 3). This region is filled with gas ionized by the AGN (as seen by MUSE). Evidence for a similar effect in other GASP jellyfish galaxies is present and is currently under investigation.

3. Star formation

The effects of RPS on the star formation activity are variegated and in a sense counterintuitive, since RPS removes gas which is the fuel for the formation of new stars.

On a galaxy-wide scale, generally the star formation rate (SFR) in the disks of galaxies undergoing stripping is slightly but significantly enhanced with respect to undisturbed galaxies of similar mass, i.e. galaxies undergoing stripping tend to lie above the SFR-stellar mass relation (Vulcani *et al.* 2018b, Fig. 4). Moreover, jellyfish galaxies follow the mass-metallicity relation of non-stripped cluster galaxies, with metallicities higher than

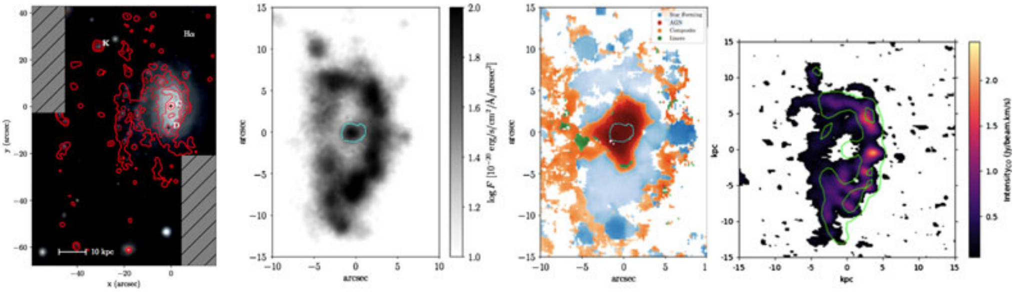

Figure 3. Left. The jellyfish galaxy JO201 Hα contours superimposed on the stellar image. The long extraplanar tails of ionized gas are visible (Bellhouse *et al.* 2017, 2019). Other three panels: a zoom on the disk of (from left to right) NUV emission, ionization source map and CO map (George *et al.* 2019). The 8 kpc central hole in UV and CO emission corresponds to the AGN-powered Hα emission.

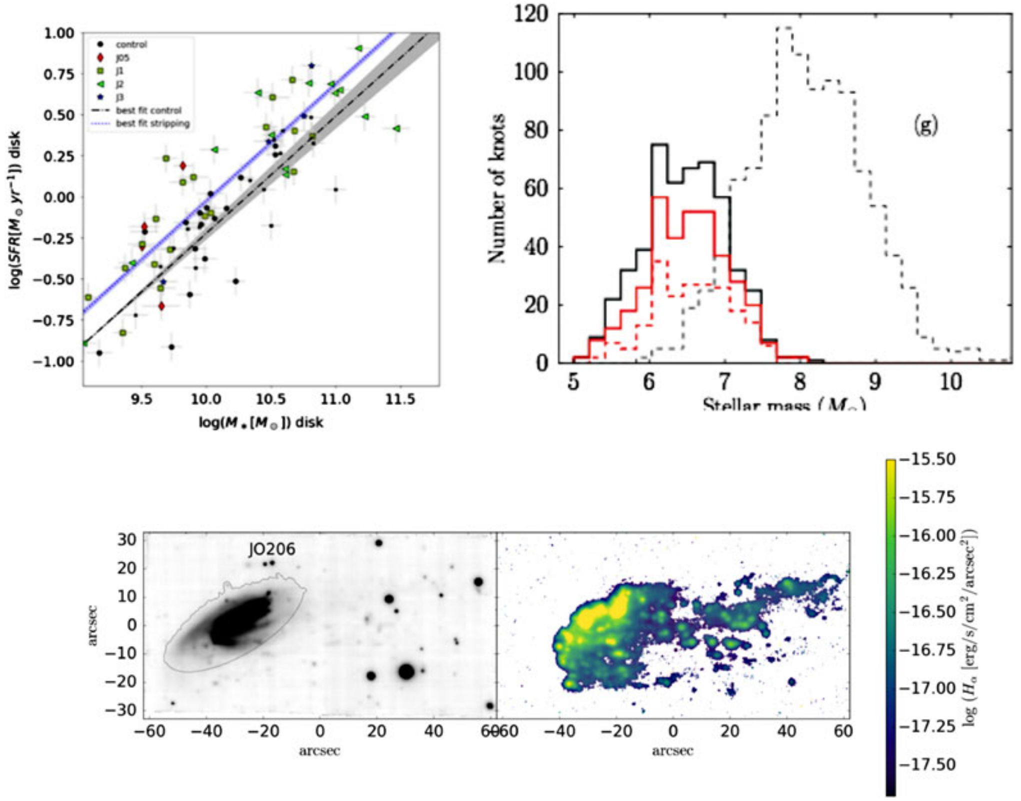

Figure 4. Top left: Star formation rate-stellar mass relation for disks of jellyfish galaxies compared with undisturbed galaxies, from Vulcani *et al.* 2018b. Top right: Stellar mass distribution of star-forming clumps in the tails of jellyfish galaxies as solid histograms (red: only clumps that are star-forming according to the BPT diagrams; black: all clumps). For comparison, the dashed histogram is for clumps in the disks. Bottom: the jellyfish galaxy JO206 with its 90kpc-long tail of Hα emitting gas (right), and its optical image dominated by the stellar disk (left). The star-forming clumps stand out in the Hα image, where also the diffuse emission is visible.

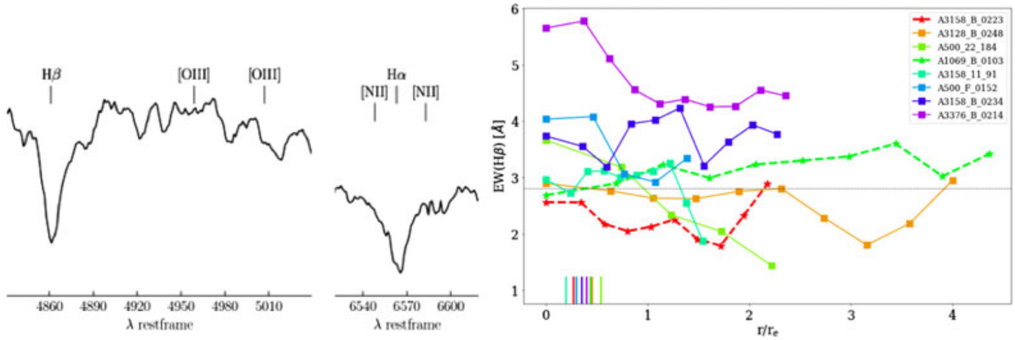

Figure 5. Left: Strong Balmer absorption lines in the outskirts of jellyfish disks, where gas has already been stripped (from Gullieuszik *et al.* 2017). Right: The galactocentric radial distribution of the Hβ equivalent width in absorption in GASP post-starburst/post-starforming galaxies. The vertical bars at the bottom of the right panel indicate the size of 1 kpc in units of r_e for each galaxy. From Vulcani *et al.* (2020).

field galaxies of similar mass (Franchetto *et al.* 2020). Even more surprising is that new stars can form in situ in the tails of stripped gas. This was already evident from UV studies (e.g. Smith *et al.* 2010; Hester *et al.* 2010), and UV+Halpha studies (e.g. Boselli *et al.* 2018; Abramson *et al.* 2011), but integral-field spectroscopy observations have allowed us to ascertain the presence of star formation in the tails and study its properties in an unprecedented way (Merluzzi *et al.* 2013; Fumagalli *et al.* 2014; Fossati *et al.* 2016; Consolandi *et al.* 2017; Gullieuszik *et al.* 2017; Moretti *et al.* 2018a; Bellhouse *et al.* 2019; George *et al.* 2018). In GASP, the dominant ionization mechanism in the long extraplanar Hα-emitting tails is photoionization by young massive stars (Poggianti *et al.* 2019a). This star formation takes place in Hα-bright, dynamically cold star-forming clumps formed in-situ in the tails, which have Hα luminosities typical of giant and supergiant HII regions (e.g. like 30Dor in the LMC) and typical stellar masses $10^6 - 10^7 M_\odot$ (Fig. 4). Are we witnessing the formation of globular clusters and/or Ultra Compact Dwarf galaxies? High spatial resolution studies are needed to determine the nature and fate of these objects (Cramer *et al.* 2019). The magnetic field measured for the first time in a long jellyfish tail has been found to be highly ordered and aligned with the tail direction. Such field, preventing heat and momentum exchange, may be a key factor for allowing the star formation in the tails (Mueller *et al.* 2020).

Another puzzle is the origin of the inter-clump, diffuse ionized emission in the tails, which represents on average 50% of the tail Hα emission (Poggianti *et al.* 2019a). The line ratios of this diffuse ionized gas (DIG) indicate that there are areas in the tails where the ionization is powered by SF (possibly due to photon leakage from nearby star-forming clumps, with an average escape fraction of ∼18%), but in some cases there is an additional (in a few cases, dominant) source of ionization, as testified by an [OI]λ6300 excess. Most probably this is due to the interaction with the hot intracluster medium in which the tail is embedded: either mixing, or thermal heating or shocks give a major contribution to the tail ionization in the jellyfish galaxy JW100 (Poggianti *et al.* 2019b), and this might be the case also for other jellyfish examples for which line ratio data is missing (Boselli *et al.* 2016).

After gas is removed by ram pressure, star formation comes to an end. A clear signature for a recent truncation of the star formation activity are the strong Balmer lines in absorption typical of post-starburst/post-starforming spectra. Such a signature is present in the outer regions of the disk of several jellyfish galaxies (e.g. Gullieuszik *et al.* 2017; Poggianti *et al.* 2019b) and is observed throughout the disk of those non-starforming

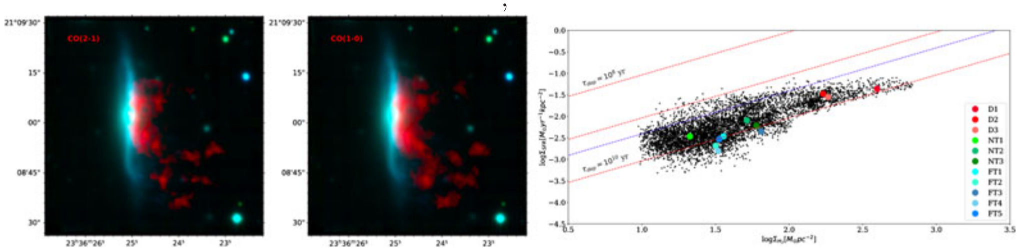

Figure 6. Left and center: CO(2-1) and CO(1-0) emission on top of the I-band image of the galaxy JW100. Right: SFR surface density versus H_2 surface density (1kpc scale) for spaxels of JW100, with a few regions of interest in the disk and tails highlighted. In the right panel, the red dashed lines are fixed depletion times (10^8, 10^9, 10^{10}yr from top to bottom), while the blue dashed line is the average relation for normal nearby disk galaxies at 1 kpc resolution. From Moretti *et al.* (2020).

galaxies that have recently finished to be stripped (Vulcani *et al.* 2020) (Fig. 5). These are totally devoid of emission lines, are typically located between 0.5 and 1 cluster virial radii (Owers *et al.* 2019; Vulcani *et al.* 2020) and have been quenched outside-in (the disk outskirts first) as expected in the ram pressure stripping scenario (Gavazzi *et al.* 2013).

4. Multi-phase gas

The number of ram pressure stripped galaxies with CO data is still rather small, but a picture is emerging: large masses of molecular gas have been detected both in disks and tails (Jáchym *et al.* 2014, 2017, 2019; Verdugo *et al.* 2015; Lee & Chung 2018; Moretti *et al.* 2018b, 2020). Following the old debates about whether the molecular gas can be stripped by ram pressure (Kenney & Young 1989; Boselli *et al.* 1997, 2014), the ALMA resolution has recently allowed to study large individual CO clumps/complexes of 10^6–$10^9 M_\odot$ masses of H_2 in the tails (Jáchym *et al.* 2019; Moretti *et al.* 2020). These studies suggest that while the cold gas observed close to the disk may be stripped, that observed further out in the tail forms there (see also Verdugo *et al.* 2015).

The amount of molecular gas in some jellyfishes is impressive, ($>10^9$–$10^{10} M_\odot$). The GASP galaxy JW100 contains $2.5 \times 10^{10} M_\odot$ of molecular gas (8% of the galaxy stellar mass), of which 30% is in the tail (Fig. 6, Moretti *et al.* 2020). Interestingly, the CO-star formation efficiency, defined as the ratio between the SFR and the molecular gas mass, is low, both on the galaxy scale and on a 1kpc spatially resolved scale, yielding depletion timescales up to 10^{10} yr (e.g. Vollmer *et al.* 2008; Jáchym *et al.* 2014; Verdugo *et al.* 2015; Moretti *et al.* 2018b, 2020, see Fig. 6).

In the tails there is a general correspondance between the spatially resolved distribution of the various tracers related to star formation (UV light, Hα emission and CO emission), but it is also possible to observe directly the "star formation sequence", with CO-only clumps, CO+Hα+UV clumps, Hα+UV and UV-only clumps, representing the different stages of the star formation process (Poggianti *et al.* 2019b).

As far as the neutral gas is concerned, HI observations paved the way to ram pressure studies, with milestones results showing the deficiency of HI in cluster galaxies (Haynes *et al.* 1984; Cayatte *et al.* 1990; Vollmer *et al.* 2001; Chung *et al.* 2009, to name a few). However, the number of jellyfish galaxies with multiwavelength data, probing neutral, molecular and ionized gas in the same system, is very limited, thus the origin and the conditions allowing the presence of multi-phase tails are still to be clarified. Generally, when an Hα tail has been observed, sufficiently deep HI data has also revealed a neutral gas tail. However, the morphologies of the Hα and the HI tail can be very different (see Fig. 7 for three example galaxies), and the kinematical decoupling of HI and Hα can be

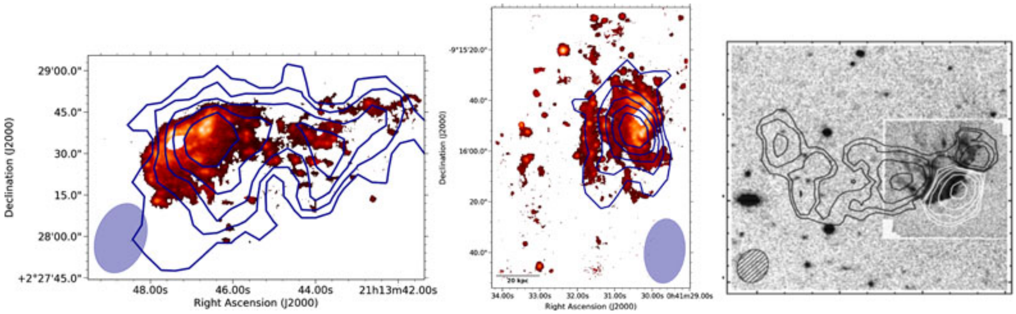

Figure 7. HI contours on top of the MUSE Hα image (plus the optical broad band image outside of the inset in the right panel) of three GASP jellyfish galaxies (from left to right, Ramatsoku *et al.* 2019, 2020 and Deb *et al.* 2020). In the right panel, the black contour is HI in emission and the white contour in absorption. The HI absorption is due to neutral gas along the line of sight between us and the central AGN. In some cases the HI and Hα tails are roughly co-spatial (left panel, tails are 90-kpc long), sometimes the Hα is much more extended than the HI (middle), and sometimes it is the opposite (right).

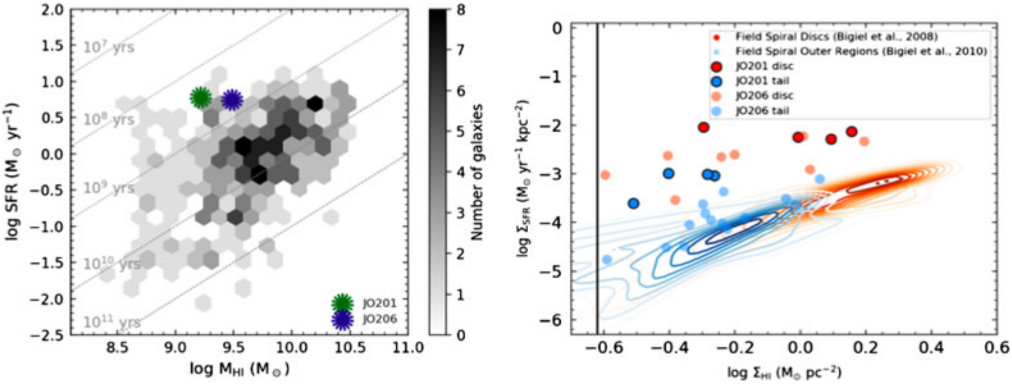

Figure 8. Left: SFR vs HI mass for two GASP jellyfish galaxies (green and blue stars), compared with a control sample of spirals. Right: SFR and HI surface densities of the disks and tails (separately) of the same galaxies, compared with field spirals disks and outskirts. The contours in the right panel are for the inner regions (orange) and outer regions (blue) of field spiral galaxies, both convolved with the HI beam. From Ramatsoku *et al.* 2020.

significant (Deb *et al.* 2020). The GASP jellyfish galaxies for which HI data is available suggest that a) during the jellyfish phase these galaxies still possess large amounts of HI gas (they are only slightly HI deficient, Ramatsoku *et al.* 2020), but the HI is clearly displaced from the disk, spatially and/or kinematically, and b) there is an excess of SFR for the HI content, compared to normal spirals, both globally and on a 1kpc scale (Fig. 8). In other words, the HI-star formation efficiency (ratio of SFR over HI mass) is higher than in normal spirals. Thus, to recap, the SFR is in excess with respect to both the HI content and the stellar mass, but the CO emission is in excess with respect to the SFR. As a consequence, in jellyfish galaxies the star formation efficiency is unusually low for molecular gas, but unusually high for neutral gas, suggesting a very efficient transformation of neutral into molecular gas in these systems (Moretti *et al.* submitted).

We have no space here to deal with tails at yet other wavelengths (X-ray; radio continuum), but we note that multi-λ studies of jellyfish galaxies including these components are growing, after the pioneering studies of e.g. Sun *et al.* (2010); Gavazzi & Jaffé (1985).

To conclude, the study of ram pressure stripped galaxies is informing us on several physical processes which are fundamental for astrophysics in general. We have mostly focused on the GASP results, but there is a broad, high quality (and growing) literature on these fascinating systems, which we hope the reader will be encouraged to explore by this contribution of ours. We apologize for not being able to report on the questions received after BP's talk, due to the difficulty in hearing them remotely. BP sincerely thanks the organizers for their kind invitation and for allowing her to give her presentation from the other side of the world.

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