Explaining the enhanced star formation rate of Jellyfish galaxies in galaxy clusters

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ABSTRACT

We study the recently observed JellyFish galaxies (JFGs), which are found to have their gas content ram pressure stripped away in galaxy clusters. These galaxies are observed to have an enhanced star formation rate of about 0.2 dex compared with a control sample of the same stellar mass in their discs. We model the increase in the star formation efficiency as a function of intracluster medium pressure and parametrize the cold gas content of the galaxies as a function of cluster-centric distance. We show that regarding the external pressure as a positive feedback results in agreement with the observed distribution of enhanced star formation in the JFGs if clouds are shielded from evaporation by magnetic fields. Our results predict that satellites with halo mass $< 10^{11} \, M_\odot$ moving with Mach numbers $M \approx 2$, and inclination angles below 60 deg, are more likely to be detected as JFGs.

Key words: methods: analytical – galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: evolution – galaxies: groups: general.

1 INTRODUCTION

Ram pressure stripping (RPS) of the gas content of the galaxies entering a cluster-like environment (Gunn & Gott 1972) have long been observed (Kenney, van Gorkom & Vollmer 2004; Chung et al. 2007; Boselli et al. 2014; Brown et al. 2017; Hayashi et al. 2017), and modelled in numerical simulations (Mayer et al. 2006; Roediger & Brüggen 2007; Tonnesen & Bryan 2009; Steinhauser, Schindler & Springel 2016; Quilis, Planelles & Ricciardelli 2017; Ruggiero & Lima Neto 2017; Safarzadeh & Scannapieco 2017; Yun et al. 2019). However, depending on the density and size of the stripped gas clouds, these clouds can survive for sufficiently long time in the cluster environment to form stars.

Extreme examples of such galaxies have been observed and named Jellyfish galaxies, hereafter JFGs (Poggianti et al. 2016). These galaxies are found in all clusters and at all cluster-centric distances. JFGs show an enhanced level of star formation both in their disc and their tails (Vulcani et al. 2018) that depends on how gas-rich the satellite is when it enters the cluster, and on how fast the gas is being stripped away.

The enhancement of the star formation under the external pressure in galaxy clusters has been studied previously. Ramos-Martínez, Gómez & Pérez-Villegas (2018) showed that in interaction of a face-on disc with the intracluster medium (ICM), gas from the outskirts of the disc flows towards the centre leading to high gas surface densities and therefore higher star formation rate (SFR).

Bekki, Owens & Couch (2010) showed that the strong compression of cold gas in gas-rich cluster members leads to a starburst phase of the satellites when the ICM pressure is boosted in cluster merging events. Bieri et al. (2016) showed that AGN feedback can act as a positive feedback by overpressurizing the star-forming regions of a galaxy and therefore leading to a higher SFR. Bekki (2013) showed that the impact of ram pressure on the star formation activity of a satellite would depend on the pericenter distances of its orbit, the inclination angles of the disc, and the halo mass dependence. Bekki (2013) showed that after pericentre passage, the SFR could increase or decrease depending on the satellite’s halo mass. Kapferer et al. (2009) found that the enhanced SFR due to RPS shows up in the wake of the galaxy rather than the disc and should be a more sensitive function of the ambient density than the relative velocity. On the other hand, Tonnesen & Bryan (2009) have found that only low ram pressures can compress the gas into high-density clouds and therefore lead to higher SFR, while high ram pressure will likely strip the gas rather than compress it.

Here we focus on the timespan during which the cold gas is being stripped and show how to calculate the elevated SFR in the satellite prior to full stripping of the gas (Rafieferantsoa, Davé & Naab 2018). We assume magnetic insulation of the molecular clouds in the disc from the hot ICM as inferred in cold fronts within the ICM (Vikhlinin, Markevitch & Murray 2001).

The structure of the paper is as follows. In Section 2 we show how RPS can act as a positive feedback mechanism for increasing the star formation efficiency in the satellites’ disc. In Section 3 we show how integrating this positive feedback with the giant molecular...
cloud mass function can lead to the observed increase in the SFR of JFGs, and in Section 4 we discuss the implications and predictions of our model.

2 RAM PRESSURE AS A POSITIVE FEEDBACK

The SFR of a galaxy is closely related to its gas surface density (Kennicutt 1998). The gas content of the satellites depends on their halo mass and redshift. Main-sequence galaxies are observed to be more gas rich at higher redshifts (Daddi et al. 2010;Tacconi et al. 2010) with large cold gas fractions, $f_{gas} \approx \frac{M_{gas}}{M_{tot}}$ (Geach et al. 2011; Narayanan, Bothwell & Davé 2012; Popping et al. 2012; Morokuma-Matsui & Baba 2015; Popping et al. 2015).

In order to construct a stellar and gas disc of the satellites, we assume the cold gas is in the form of an extended exponential disc profile with gas scale radius $R_{d}^{g} = 1.7 R_{d}^{e}$ (Popping et al. 2015), and a stellar radius, $R_{d}^{s}$ computed as $R_{d}^{s} = R_{d}^{e}/1.67$, where $R_{d}^{e}$ is the half-light radius of the stellar disc. $R_{d}^{e}$ is related to halo mass of the galaxy as, $R_{d}^{e} = 0.015 R_{200}(M_{halo})$ (Kravtsov 2013), where the halo radius ($R_{200}$) is defined as enclosing an overdensity of 200 times critical density of the universe at a given redshift. Therefore, knowing the halo mass of a galaxy, one can estimate the cold gas scale length which would be related to the maximum size of the cold clouds that would be stripped from a satellite. We estimate the stellar disc mass ($M_{d}$) given a halo’s redshift and mass following Behroozi, Wechsler & Conroy (2013).

When a satellite galaxy enters the hot ICM, it encounters the thermal and ram pressure of the ICM given by:

$$P_{tot} = \rho c_{s}^{2}(1 + M^2) \cos(\theta)$$

where $\rho_{ICM}$ is the ICM density, $c_{s}$ is the sound speed of the ICM, and $M$ is the Mach number of the satellite moving in the ICM. We denote the angle between the angular momentum vector of the satellite’s disc and its direction of motion in the cluster as $\theta$, such that $\cos(\theta) = 1$ for a face-on configuration. We assume a fiducial Mach number of $M = 1.4$ for the satellites (Faltenbacher et al. 2005), and we consider a maximum Mach number of $M = 2$ corresponding to those satellites moving with approximately escape velocity of the cluster. The external pressure acts as a positive feedback and triggers star formation in the disc (Swinbank et al. 2011). The resulting SFR depends on the ratio of the external pressure and the interstellar medium (ISM) pressure of the satellite’s disc (Elmegreen & Efremov 1997). The ISM pressure of the satellite before infall is given by:

$$P_{ISM} \approx \frac{\pi}{2} G \Sigma_{e} \left( \Sigma_{e} + \left( \frac{\sigma_{e}}{\sigma_{s}} \right) \Sigma_{s} \right),$$

where we model both stellar and gas surface densities as exponential profiles and assume $\sigma_{e} \approx \sigma_{s}$. Fig. 1 shows the ISM pressure for satellites of different halo mass pre-infall.

To compute the ram pressure that the satellite encounters, we model our galaxy cluster with gas density profile similar to A1795 as $\sim 10$ of the known population of the JFGs have been detected in this galaxy cluster (Poggianti et al. 2016). The gas density and temperature profile of A1795 is modelled following Vikhlinin et al. (2006). We compute the ram pressure assuming that the satellite moves in the ICM with Mach number $M \approx 1.4$.

The ratio of the ICM pressure to the ISM pressure of the disc of the satellites at the location of the effective radius of the disc is shown in Fig. 2. The regime where the pressure ratio is greater than 1, we expect positive feedback to enhance the SFR in the satellites’ disc.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{The ISM pressure of galaxies with different halo masses pre-infall. The gas fractions are assigned given the stellar mass of the galaxy and its redshift following Popping et al. (2015). The stellar masses are assigned based on Behroozi et al. (2013).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{The ratio of the ICM pressure to the ISM pressure of the disc of the satellites at the location of the effective radius of the disc. The gas density and temperature profile of A1795 is modelled following Vikhlinin et al. (2006). We have assumed $M = 1.4$ for the satellites.}
\end{figure}

3 ENHANCED STAR FORMATION EFFICIENCY

The impact of the external pressure on the star formation efficiency has been formulated in Elmegreen & Efremov (1997). High pressures increase the star formation efficiency more effectively for more massive clouds. In our case, the increase in the pressure is modelled as $P_{tot}/P_{ISM}$. In order to get a sense of what types of...
clouds contribute to the enhancement of the star formation in JFGs, we would need to specify the giant molecular cloud (GMC) mass function.

We assume the GMC mass function of dN/dM ∝ M^{−α} with α = −2 (Hopkins 2012). The mass weighted star formation efficiency at a given pressure is computed as

$$\epsilon(P) = \frac{\int_{M_0}^{M_1} \epsilon(M, P) \frac{dN}{dM} dM}{\int_{M_0}^{M_1} \frac{dN}{dM} dM},$$

(3)

where $\epsilon(M, P)$ is computed following Elmegreen & Efremov (1997). We only consider clouds in the mass range of $M_1 = 10^6 M_\odot$ to $M_2 = 10^9 M_\odot$ to be relevant for our study, where the upper limit is based on the observations of the GMCs in the Milky Way galaxy (Rosolowsky 2005; Fukui & Kawamura 2010). Pressure is related to the cluster-centric distance (d), and therefore one can express $\epsilon(P)$ as $\epsilon(d)$.

Since the observations trace the SFR, one has to connect the enhanced star formation efficiency to SFR. We write $SFR \propto \epsilon \times M_{cold}$. Modelling the cold gas reservoir to decline with cluster-centric distance provides a reasonable physical picture. We model the depletion of cold gas mass to be approximately a smooth linear function of the cluster-centric distance such that the cold gas mass at cluster-centric distance d is $M_{cold, d}/M_{cold, field} \propto d/R_{200}$. Although more sophisticated treatment would be needed to understand how cold gas is removed from the galaxy by both stripping and star formation (Zinger et al. 2018), we proceed with this simple ansatz with two implications: (i) the lost cold gas mass reduces the internal ISM pressure of the satellite, and therefore enhances the relative pressure of the ICM to the ISM; and (ii) it directly influences the gas mass available for the star formation.

In the left-hand panel of Fig. 3 we show the ratio of the SFR of a $10^{11} M_\odot$ satellite as a function of cluster-centric distance for different values of the Mach numbers. Lines are colour coded from the lowest to the highest Mach number with dark blue to dark red. Right-hand panel of Fig. 3 shows the result for satellites of different halo mass moving with $M = 1.4$ in the ICM. A satellite with halo mass of $\sim 10^{11} M_\odot$ is more likely to be considered as a JFG. Haloes with SFR enhancement of about 50 percent are distributed over a wide cluster-centric distances but mostly found between $0.4R_{200}$ and $0.8R_{200}$ of their host cluster, in good agreement with the observations of the JFGs in OMEGAWINGS sample (Poggianti et al. 2016). Moreover, we show the impact of the inclination angle $\theta$ on the same panel. The blue dashed and dot-dashed lines indicate a situation where the inclination angle is assumed to be 45 and 60 deg, respectively, for a satellite with halo mass of $10^{11} M_\odot$. At inclinations above 60 deg, we expect the impact of the ram pressure on enhancing the SFR of the galaxy to be significantly suppressed.

4 DISCUSSION

Fujita & Nagashima (1999) studied the impact of ram pressure on the SFR of satellites in clusters and find a factor of 2 increase in SFR at pericenter distances. In their model the molecular gas is never stripped and the SFR rapidly drops near the central regions because the cold gas is stripped away and the existence of molecular clouds is truncated. Although the spirit of our method is similar to their approach, we treat differently the process and compare our results to new data on JFGs.

Scannapieco & Brüggen (2015) showed that in the absence of a shielding magnetic field layer, a cold cloud in the ICM would be disrupted on a time-scale given by:

$$t = \alpha \tau_{cc} \sqrt{1 + \frac{M}{\rho}};$$

(4)

where $\tau_{cc}$ being the cloud crushing time-scale, defined as

$$\tau_{cc} \equiv \frac{\alpha}{\chi_0^{1/2} v},$$

(5)

with $v$ is the speed of the cloud in the ICM, $R_{cloud}$ is the radius of the cloud, $\chi_0$ is the initial density ratio between the cloud and ICM, and $\alpha$ quantifying the fraction of the cloud that is disrupted after some given time. For the case of a cloud with mass of $10^5 M_\odot$, radius of 30 pc, the time it takes for the cloud to be 90 percent disrupted moving with $M = 2$ in the ICM of A1795 ranges from about 45 Myr at distances of 1 Mpc from the cluster centre, to 3 Myr at a distance of 10 kpc. These time-scales are too short with respect to the time it takes the satellite to reach the inner part of the galaxy cluster, meaning the clouds would have been largely disrupted by the ICM pressure.

The underlying assumption in our model is that the molecular clouds are shielded by magnetic fields from evaporation due to the hot ICM. Magnetic fields in spiral galaxies have two separate elements: (i) the ordered magnetic field which is at the order of a few $\mu$G, and (ii) the turbulent component that is an order of magnitude larger in amplitude (Beck 2015). Very strong magnetic fields of order of a few $\mu$G has been reported towards highly star-forming regions (Robishaw, Quataert & Heiles 2008; McBride & Heiles 2013; Han 2017) through OH masers and measures of their Zeeman splitting.

Fig. 4 shows the comparison between the energy density in the magnetic field of the GMCs and the pressure encountered in the ICM. Estimating the magnetic field energy density, $t_{bg} = B^2/8\pi$ and equating it to the total pressure from ICM on a satellite moving with Mach number of $M = 1.4$ we find that a GMC magnetic field strength of 30 $\mu$G can shield the molecular clouds down to about 400 kpc in a host cluster of mass $\sim 2 \times 10^{14} M_\odot$. This level of magnetic field is only expected in GMCs and is separate from the ordered magnetic field that is of the order of a few $\mu$G.

Our results are consistent with the observed distribution of JFGs in IllustrisTNG Gravity and MHD simulation (Yun et al. 2019) where the JFG candidates are shown to occupy the higher end of supersonic velocities and reside in smaller satellite haloes masses. In our analysis we have parametrized the ISM pressure of the satellites assuming they resemble disc galaxies in the local universe. The cold gas fraction of haloes increase with redshift, which results in an increase in their ISM pressure. If we model the satellite to resemble those at $z = 0.1$ before infall, we would not see an increase in the SFR in their disc since $P_{tot}/P_{ISM}$ is low for such systems. Therefore, we require the JFGs to be late infallers for our model to work. Moreover, we predict no JFGs to be present at short cluster-centric distances, which is observed in simulations (Yun et al. 2019) and observations (Poggianti et al. 2016).

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Enhanced SFR in JFGs

Figure 3. Left-hand panel: the ratio of the SFR of the satellites as a function of cluster-centric distance to the SFR of the satellite in the field, shown for a satellite with halo masses of $10^{11} M_\odot$ moving in a host galaxy cluster of mass $\sim 2 \times 10^{14} M_\odot$. Lines are colour coded from lowest to the highest corresponding to Mach numbers values ranging from $M = 1$ to $M = 2$ which is about maximum seen for satellites in galaxy cluster simulations (Faltenbacher et al. 2005). We are showing the enhancement of the integrated SFR over the entire disc. Right-hand panel: results for different satellite halo masses assuming the satellite is moving with $M = 1.4$. The blue dashed and dot-dashed lines show the case where the inclination angle of the satellite is assumed to be 45, and 60 deg, respectively. At inclinations above 60 deg we expect the enhancement of the SFR in the disc to be significantly suppressed.

Figure 4. The ICM pressure for a satellite moving with $M = 1.4$ (2) is shown in solid (dashed) black lines, respectively. The red horizontal lines indicate the magnetic field energy density in the GMCs for different assume values as labelled close to each line. GMC magnetic field strength of $30 \mu G$ can shield the molecular clouds down to about 400 kpc in a host cluster of mass $\sim 2 \times 10^{14} M_\odot$ given the Mach number of the satellite.

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