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Asymmetric Star Formation Efficiency Due to Ram Pressure Stripping

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Abstract: Previous works have shown that a dense cluster environment affects satellite galaxy properties and accelerates or truncates their evolutionary processes. In this work, we use the EAGLE simulation to study this effect, dissecting the galaxies in two halves: the one that is falling directly to the cluster (leading half) and the one behind (trailing half). Considering all galaxies within the virial radius of the most massive groups and clusters of the simulation ($M_{halo} > 10^{13.8}[M_{\odot}]$), we find that on average the leading half presents an enhancement of the star formation rate with respect to the trailing half. We conclude that galaxies falling into the intra-cluster medium experience a boost in star-formation in their leading half due to ram pressure. Sparse observations of jellyfish galaxies have revealed visually the enhancement of the star formation in the leading half. In order to confirm this effect statistically using observations, different cases must be investigated using the simulation as a test dataset.

Keywords: galaxy; clusters; ram pressure; jellyfish galaxies

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1. Introduction

Galaxy clusters have been extensively used to study galaxy evolution because they allow us to discern between nature and nurture galaxy evolutionary processes [1,2]. For simplicity, hereafter, we refer to the intra-cluster medium (ICM) as the hot medium of both groups and clusters of galaxies. As galaxies plunge into the ICM, they experience different effects from their surrounding environment, including ram pressure (RP) and tidal stripping. These can produce a range of changes on the galaxy properties from gas loss to enhanced star formation (SF) activity due to the increased pressure acting on the disc of the galaxy. In observations, the effect of RP is studied in galaxies that are being stripped in clusters, identified via their distorted morphologies [3,4]. This proceeding presents an alternative method that uses all the galaxies that are identified as cluster members to detect RP stripping in a statistical way. The simplest way to detect this effect is by studying asymmetries in the galaxy properties by dividing each satellite in two halves: the one that faces the medium as it moves through the ICM, to which we will refer to as the leading half; and the one facing the opposite way, the trailing half of the galaxy. If the timescale of the effect of RP stripping on the SF activity is shorter than the dynamical timescale of the disc, the enhancement of the SF could be more prominent in the leading half, which is exposed directly to the RP effect. If this is the case, we would expect to find different SF properties/colours in the leading half with respect to the trailing one.

In this article, the results using the EAGLE simulation to detect these effects are presented. We measure the properties in the leading and trailing halves and study their differences using large samples of $z = 0$ galaxies in clusters and groups. We use the largest box of the EAGLE simulations in order to identify enough massive groups/clusters, in the range of $M_{halo} > 13.8[M_{\odot}]$, and concentrate on large satellites, with more than 100 particles, to avoid resolution problems. M_{halo} refers to the total mass of the halo, calculated as the sum of the mass of all particles. For the mass scale of the clusters and groups, we have used an overdensity of M_{200}^{crit} as stated in the EAGLE collaboration website. In Section 2, the dataset used is described in detail. In Section 3, the results are presented. In Section 4, we discuss our results and further prospects. Our conclusions are given in Section 5.

2. Materials and Methods

2.1. EAGLE Simulation

The EAGLE project is a suite of hydrodynamic simulations immersed in a ΛCDM cosmology. It uses up to seven billion particles per individual simulation to follow the physics of the galaxy processes, considering dark matter and gas particles. The gas particles fall into the centres of dark matter haloes, depending on how they have cooled and whether they reach a density greater than a certain threshold, they can be converted into star particles or not. The rate at which stars are formed is determined by the thermodynamic conditions of the medium. The simulations follow different feedback mechanisms, such as core collapse supernovae, exploding massive stars and AGN (Active Galactic Nuclei), via bursting supermassive black holes, etc. For further details please refer to [5].

2.2. Halving the Galaxies

We analyse all $z = 0$ galaxies of the largest box simulation RefL0100N1504 that reside within one virial radius of groups of mass greater than $10^{13.8} M_{\odot}$. These groups are found using the multistage procedure, based on a friends of friends algorithm, described in [6].

We investigate two cases, first halving the galaxy with respect to the plane normal to its position vector and secondly to its velocity vector, both with respect to the centre of the mass of the host group. Hereafter, the former is dubbed the observational case; it refers to the measurements that can be performed in typical observations, while the second is dubbed simulation case which can only be measured when the velocity of the centre of the mass is known. These vectors and planes are shown in the cartoon representation of the problem, in the left panel of Figure 1.

The right panel of Figure 1 shows a three-dimensional view of an EAGLE galaxy cut in two halves, according to the plane perpendicular to the velocity vector, with respect to the centre of mass of its host. The left panel schematizes the vectors and planes used to halve the galaxies.

The falling angle is defined as the angle between the position and the velocity vector of the galaxy, both relative to the brightest cluster galaxy (BCG) of each cluster,

$$cos(180 - \phi) = \frac{(\vec{r}_{CM} - \vec{r}_{BCG}) \cdot (\vec{v}_{CM} - \vec{v}_{BCG})}{||\vec{r}_{CM} - \vec{r}_{BCG}|| \, ||\vec{v}_{CM} - \vec{v}_{BCG}||}. \quad (1)$$

The EAGLE consortium provides a diversity of physical properties for each gas, dark matter, and stellar particle. We introduce a new quantity estimated with the star formation rate (SFR) and mass of the gas particles, hereafter dubbed SFR enhancement

$$\Delta SFR_E^w \equiv \frac{SFR^w(LH) - SFR^w(TH)}{SFR_{total}^w}. \quad (2)$$

This corresponds to the mass-weighted SFR that avoids effects from intrinsic asymmetries between the two halves, such as different number of particles, gas masses, etc., which could dominate the SFR difference. The normalization term SFR^{w}_{total} corresponds to the mass-weighted SFR of all gas particles. Within the sample analysed, the leading half of the galaxy that is shown in Figure 1 presents a typical SFR enhancement of 10% with respect to its trailing half.

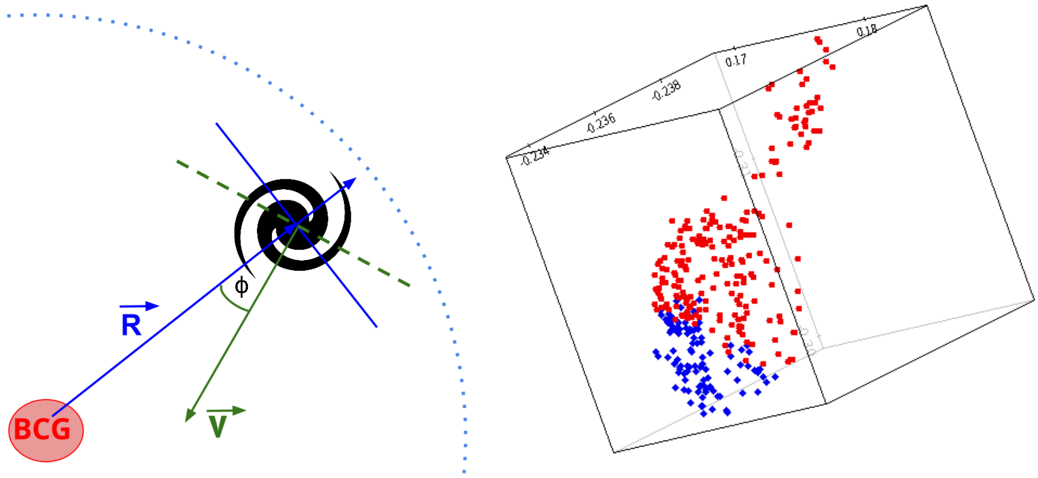

Figure 1. Visualization of EAGLE galaxies. (**Left**): A schematic representation of the vectors and planes used to halve the galaxies. In blue (green) the position (velocity) vector is shown, perpendicular to it the blue solid (green dashed) line schematizes the cut plane of the *observational (simulation) case*; (**Right**): Three-dimensional view of an EAGLE galaxy divided in two parts according to the plane perpendicular to the velocity vector measured with respect to the position of the brightest cluster galaxy (BCG). Blue diamonds belong to the leading part, while the red dots correspond to the trailing half. The unit of each side of the cube is mega-parsecs.

3. Results

In what follows, we study the SFR enhancement for the two cases described previously. Eighty galaxies are analysed in total, with typically 500 gas particles per galaxy.

3.1. Simulation Case

Figure 2 shows the SFR enhancement as a function of the falling angle. The median of the SFR enhancement is above zero, with a median value of 0.1 (red line). The positive enhancement shows that SFRs are higher in the leading half of galaxies in groups. Most of the galaxies (80%) present a positive enhancement, with a few reaching up to $\Delta SFR^{w}_{E} \sim 0.6$. This last case corresponds to the typical jellyfish galaxies (confirmed visually in a few examples).

3.2. Observational Case

In the case of real observed galaxies, it is challenging to obtain the three-dimensional velocity vector of satellites to define the leading and trailing halves. Here, the approach is simplified and the most simple observational case is discussed. The differences between the half of the satellite that points to the centre of the group/cluster, are compared to the other half. As it is shown in Figure 2, the leading half shows higher SFRs with respect to the trailing half for falling angles lower than 100°. Although this would not be possible to know from observations, it helps to understand where the signal would be coming from. The median value tends to zero (red line). In this observational approach, the velocity vector is unknown, as well as the falling angle. Hence, the median value of the enhancement is the only value measurable using observations. A strategy to detect this effect in observations still needs to be devised, and we present a few examples in Troncoso et al. (in prep).

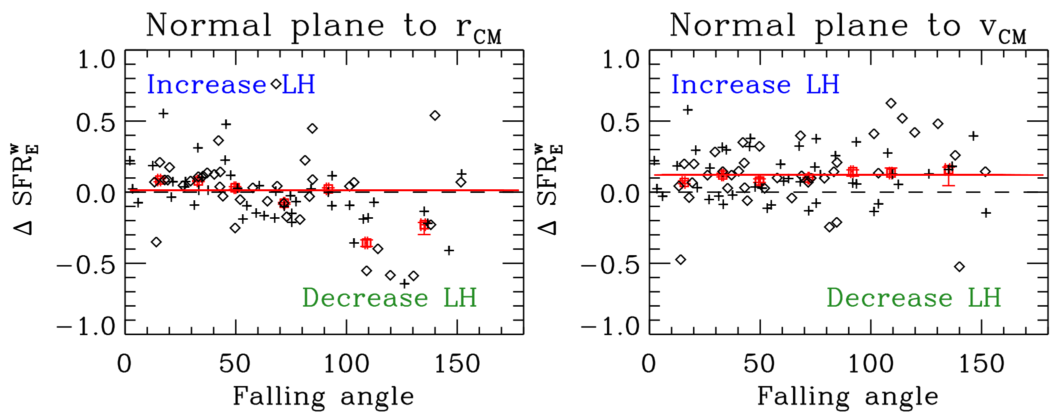

Figure 2. SFR differences between the leading and trailing halves of the galaxy as a function of the falling angle. **Left** panel shows the results halving the galaxy in the plane perpendicular to the position of its centre of mass (*observational case*), while the **Right** panel shows the differences halving the galaxy in the plane perpendicular to the velocity vector of its centre of mass, relative to the BCG (*simulation case*). Diamonds indicate the galaxies residing on relax clusters, while the crosses show the galaxies of less relaxed systems. The errors correspond to the one sigma percentiles of each bin divided by the number of galaxies of each bin. The red line shows the median of all measurements.

3.3. Dynamical State of the Host Clusters

We divide the galaxy sample in equal size according to the dynamical state of its host cluster. To determine the relaxation level of each cluster, we measure the position shift between the centre of mass and potential and normalized to its virial radius. The media of the SFR enhancement is pretty similar for both samples: for galaxies residing in the relax cluster, it is $0.10^{+0.22}_{-0.18}$ and for the less relax cluster, it is $0.12^{+0.23}_{-0.16}$. In Figure 2, the diamonds indicate the galaxies residing in relax clusters, while the crosses show the galaxies of the less relax clusters. Yet, the most extreme orbits with the highest SFR enhancements, with the small falling angles or receding galaxies, are found more frequently on galaxies residing in merging clusters, and relax clusters, respectively.

4. Discussion

We have measured the *SFR* differences between the leading and trailing halves of cluster galaxies in groups and clusters considering different falling angles. The difference between the *simulation* and the proposed *observational* case is striking. By construction, the difference between the *observational* and *simulation* case increases with the falling angle. The *simulation case* shows that there is an enhancement of SFR in the leading half, suggesting that RP compression is boosting its SFR, while the *observational case* suggests that the RP compression is not producing any measurable change; i.e., the mean value of the enhancement is zero for the *observational case*, while for the *simulation case* it is positive. Galaxies with falling angles in the range $90 < \phi < 180$ are receding from the cluster centre. Small falling angles were preferably found in cluster galaxies. In the *observational case*, galaxies falling with angles above 100° tend to show a negative SFR enhancement. This result provides a caveat for observational works using the simplistic case proposed here aiming to detect RP stripping and it provides motivation to find the proper observable using hydrodynamic simulations. In a forthcoming article, the SFR enhancement will be analysed as a function of the galaxy global properties and redshift.

By dividing the sample according the dynamical state of the host cluster, we do not measure a difference of the media SFR enhancement in relax and less relax clusters. The orbits with small falling angles preferably occur on less relax clusters, while the receding galaxies are observed frequently on relax clusters.

In the $z = 0$ EAGLE Universe, the largest differences were measured considering the most massive groups (i.e., $10^{13.8} M_{\odot}$). Yet, the differences in SFR are small, lower than $\sim 1\, M_{\odot}\,\mathrm{yr}^{-1}$.

Even if the *simulation case* was applicable in observations, it would be challenging to measure these differences with the available integral field units (IFUs) because, to achieve accurate SFRs it is necessary to detect H_{β} with a high signal to noise. Typically, this involves integrations that are larger by a factor of three–four times higher than for H_{α} depending on the galaxy extinction. Since in this work we are proposing to integrate the SFR in each half, and not use the individual spaxels, the signal will increase as $\sqrt{N_{spaxels}/2}$, where $N_{spaxels}$ is the total number of spaxels in the IFU.

5. Conclusions

Using the EAGLE simulation, we find an enhancement of the SFR in the part of the galaxy that is facing the intra-cluster medium (leading half) with respect to the trailing one. The differences between the leading and trailing halves of other physical properties, and their evolution with redshift will be presented in a forthcoming article (Troncoso et al. in prep). To confirm these results with observations, it is necessary to study different observational cases using the simulation as a testbed, because projection effects can mislead the final conclusions, as it was shown in this work. This is a clear example and motivation to find the proper observables using hydrodynamical simulations.

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Conflicts of Interest: The authors declare no conflict of interest.

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