The Star Formation Distribution in Interacting Galaxies

Scientific Justification (max 1200 words)

Galaxy interaction is a fundamental process that has played a pivotal role in galaxy evolution throughout cosmic history. It induces severe morphological disturbance, the formation of tidal features ([Toomre & Toomre 1972](https://ui.adsabs.harvard.edu/abs/1972ApJ...178..623T/abstract)), large increases in star formation ([Moreno et al. 2021](https://ui.adsabs.harvard.edu/abs/2021MNRAS.503.3113M/abstract)) which often leads to quenching ([Smethurst et al. 2018](https://ui.adsabs.harvard.edu/abs/2018MNRAS.473.2679S/abstract)) and, it has been argued, leads to the ignition of nuclear activity in the galactic core ([Ellison et al. 2011](https://ui.adsabs.harvard.edu/abs/2011MNRAS.418.2043E/abstract)). However, how the underlying parameters of an interaction (the mass ratio, relative sizes, impact parameter, etc) influence which processes occurs or which tidal features form is poorly understood.

A recent project which attempted to understand this was that of the Galaxy Zoo: Mergers project ([Holincheck et al. 2016](https://ui.adsabs.harvard.edu/abs/2016MNRAS.459..720H/abstract)). This was a citizen science project which utilised a highly efficient N-body simulation to constrain fourteen underlying parameters of a sample of sixty major interacting galaxies. This project was successful in parameterising each of them, and was able to recover their merger history. We have been developing new software to mirror this process automatically. This will allow us to apply their constraining methodology to a much larger sample, without having to wait years for the citizen scientist outputs.

The code we have developed (O’Ryan et al. in prep [link](https://drive.google.com/file/d/1fTEZiE36SckEwuHzxB5mdcP--brz62yq/view)) is conducting a flux and morphological matching in order to find the best fit underlying parameters of these sixty interactions (and their errors). However, there is a key component of an interaction we are missing: that of the velocity. By not knowing where the tidal features are moving, we find multiple degenerate best fit solutions from our models: particularly in the orientation of the interaction. Attaining this information on a subset of our sample (fourteen systems) would allow us to quantify the improvement our method can attain.

A preliminary investigation into the improvement of our algorithm for parameterising interacting galaxies is shown in Figure 1 for the Arp 239 interacting system. This is one of four of our interacting galaxy sample which has existing IFU data from MaNGA ([Bundy et al 2015](https://ui.adsabs.harvard.edu/abs/2015ApJ...798....7B/abstract)). The Figure shows contours of increasing probability for the best fit parameters of the system. While there is no appreciable improvement in the sizes and masses of the system, there is significant improvement in position, velocity and orientation of the interaction. In fact, in the orientation of the system, we completely break the degeneracy with no velocity information available. **This allows us to select a single peak in parameter space of our best fit model, significantly improving its applicability.**

A second question we will answer with this proposal is that of where / if a starburst occurs in an interaction at all. Often, this question is answered with simulations. However, there is also much debate as to when in the interaction or even where in the galaxy a starburst takes place. Is it primarily at the during the interaction ([Wilkinson et al. 2018](https://ui.adsabs.harvard.edu/abs/2018MNRAS.479..758W/abstract)) or only upon coalescence ([Hopkins et al. 2013](https://ui.adsabs.harvard.edu/abs/2013MNRAS.430.1901H/abstract))? Does a starburst even happen at all ([Moreno et al. 2015](https://ui.adsabs.harvard.edu/abs/2015MNRAS.448.1107M/abstract))? Then, there is the question of where this starburst occurs. Does gas rush to the core of the galaxy and only cause a starburst there ([Bergvall et al. 2003](https://ui.adsabs.harvard.edu/abs/2003A%26A...405...31B/abstract)), or are there significant increases in star formation in the galactic disk and tidal features ([Sparre et al. 2022](https://ui.adsabs.harvard.edu/abs/2022MNRAS.509.2720S/abstract))? The simple fact of the matter is, **direct observations localising star formation in interacting galaxies is very limited and, therefore, the answer remains elusive**.

Preliminary work on this has been conducted using a subset of interacting galaxies from the [O’Ryan et al (2023)](https://ui.adsabs.harvard.edu/abs/2023ApJ...948...40O/abstract) catalogue. This is a large catalogue of interacting galaxies, that we cross matched with the COSMOS2020 ([Weaver et al. 2023](https://ui.adsabs.harvard.edu/abs/2022ApJS..258...11W/abstract)) catalogue for photometric information. We classified each interacting system into four separate stages of interaction: stage 1 - approaching; stage 2 – contact made (disturbance visible); stage 3 – past contact (tidal features formed); stage 4 – coalescing, and their total stellar masses and star formation rates investigated. The results from this (shown in Figure 2) indicates the disappearance of the red sequence of interacting galaxies in stages 3 and four. Thus, implying star formation enhancement occurs primarily later in the interaction. **However, it is important to note that these only answer one of our two questions and is also purely based on photometric fitting of these galaxies.**

The eleven systems we propose (shown in Figure 3) to observe are of a variety of stages of interaction with similar mass ratios and gas content. Two systems are in stage 1 and 2 while three are in stage 3 and 4. Often the interactions themselves are so large that observing the primary and secondary of the interaction must be done with two separate observations. This is a specific issue with stage 2 and 3 as the two galaxies are fully separate and distinct. We elect to add an additional system to stages 3 and 4 as our preliminary results indicate this is where we should observe the star formation enhancement.

To measure, and localise, the star formation throughout each galaxy we will be focused on measuring the Hα and O[III] lines in each. We will be particularly observing O[III] as this is evidence of new star formation, expected in an ongoing starburst. However, observing O[III] is difficult depending on the age of the stellar population. Hence, we will attempt to observe O[III], but recover Hα in the case it cannot be recovered. Tracing the ionised gas will not only give us a back-up proxy for where star formation is occurring, but it will also allow us to trace the line-of-sight rotational or non-rotational motion of the galaxy and its tidal features.

It is important to note that using WEAVE gives us a unique opportunity to investigate where and when a star burst occurs in interacting galaxies by looking at the most massive, fully constrained samples in the local universe. The large Field-of-View required to view these systems with an IFU (**and only available with WEAVE**) means that a full star formation or velocity map of these entire systems has never been created. With the furthest system (Heart) being at z = 0.04, the worst resolution we will achieve is 2.12kpc / fibre. With such high resolution, we will be able to map exactly where star formation is occurring in these systems, and exactly how the tidal features are moving in three dimensional space.

We believe this is an excellent pioneering use of WEAVE, to demonstrate that it can break boundaries even with well studied and understood systems. We will publish two papers from the results of this observing run. The first will be on the degeneracy breaking ability of adding velocity information to our parameterising software, and conducting a full parameterisation of all systems observed. The second will be a paper on studying precisely where and when star formation is enhanced in major, wet interacting systems.

Figure 1 Caption:

Probability distribution of the best fit parameters for the Heart (J155308.62+540950.4) interacting galaxy system. This is a stage 4 system, and one of the interacting systems proposed to be observed. Shown on the left hand side is the initial probability distribution of numerous parameters of the interaction with no velocity information available. On the right hand side is the same, but with velocity information available. AS can be seen, with velocity information from IFU data, we have a significant improvement on our constraints for the velocity, position and orientation parameters. In fact, we completely break degeneracy in the orientation parameters.

Figure 2 Caption:

Preliminary results from an upcoming work investigating the effect of interaction stage on numerous galactic parameters. In this example, we show the change in total star formation rate and stellar mass in an interacting system with stage. As can be seen, the total star formation is significantly higher in galaxies of the same mass at stages 3 and 4 compared to stages 1 and 2. This implies that the star formation enhancement expected to occur in interaction only begins to take effect once the two systems have passed each other, tidal features are forming and they exhibit severe morphological disturbance or the beginning of coalescence.

Figure 3 Caption:

The targets proposed to be observed in this observing run. In total, there are 16 targets over eleven different interacting systems. Due to the very large FoV of all WEAVE LIFUs, we are able to observe the all of these systems (except Heart) for the first time with IFUs. For six of the systems, the FoV is expected to be so large that the entire system will be covered with one observation. However, for the remaining five systems, we must observe the primary and secondary with different exposures.

Technical Justification (max 1200 Words)

The sample of interacting galaxies which our targets are drawn from are local universe major interactions (i.e. have a mass ratio of close to 1:1). The highest redshift object we will observe is a z = 0.04. This means that surface brightness dimming of the disks and tidal features of our targets will not be a problem, as they are so close. Due to how local these systems are, they have been rarely observed using IFUs, and primarily have been with spectrographs. This makes observing them with the LIFU of WEAVE an excellent opportunity, as it is the first IFU instrument with the Field-of-View (FoV) required to observe their entire disks and their tidal features.

Only two of our proposed targets, Heart and Arp 239, have been observed by MANGA. In Figure 1, we show the measured FoV of MANGA, as well as the map of the measured *H*α emission. In both systems, the FoV is too small to properly measure this emission across the tidal features of Arp 239 or even across the second nucleus of the Heart system. Figure 2 then shows the predicted FoV that will be achieved by WEAVE. As shown, they will far surpass that of MANGA, capturing the entire system of Heart as well as the tidal features in the primary and secondary galaxies of Arp 239.

We also propose to observe these systems that overlap with MANGA to utilise MANGA as a baseline for WEAVE. We will be able to quantify the improvement that WEAVE provides us in both resolution, sensitivity and in what we are missing by not also observing the tidal features of these systems. By using the redshift of each target and the measured diametres of the fibres on-sky, we anticipate achieving a resolution ranging from 0.5kpc – 2.12kpc. With such resolution, we will be able to clearly map out new star formation, stellar populations, and the kinematics occurring in the galactic disks and tidal features.

Here, discuss the expected SNR we will achieve in this project.

We will be specifically requesting that the LIFU will be operated using the green (4730Å – 5450Å) and red arm (5950Å - 6850Å) in high resolution mode. The red arm will cover all possible redshifts (of our targets) of *H*α (6562.8Å). While observing the *H*α line is a secondary priority for our second science goal, it is of utmost importance for our primary goal. We will utilise it to calculate the internal gas kinematics, and therefore, the bulk rotational and non-rotational motions within the galaxies. The blue and red arms of the LIFU have a dispersion of 0.090Å/pix and 0.11Å/pix respectively. For the two wavelength ranges we are interested in (), this translates to a resolution of ∿1 – 10 km / s. From our experience, the centroid of an emission line can be detected to 1/10th of a pixel. Therefore, internal kinematics of the galaxy will be able to characterized up to a 0.1 – 0.5 km / s. From our simulations, we expect the internal motion to vary around a few hundred km / s. This means, with the SNR we expect to reach, we will be able to accurately measure the internal velocity of the gas.

Upon correcting for the redshift in the *H*α line, any excess shift will be due to the rotational motion of the ionized gas. Therefore, it allows us to trace the rotational and non-rotational motion of material through the galactic disk and tidal features. These bulk motions are also represented in our simulations, and matching maps can be built. This will allow us to faster constrain our models for these systems, and demonstrate the degeneracy breaking capabilities of it.

In regards to our second goal, measuring SFR, we will be utilizing the green arm of the IFU. While *H*α is an indicator of star formation, significantly more evidence of recent star formation is the [OIII] doublet (4959Å and 5007Å). Where there is this emission, there is O-type stars. These stars have incredible short life spans (~10 million years), and are very luminous. Their very high luminosity causes the rapid ionization of neutral oxygen. Hence, identifying regions of high [OIII] emission will correspond to massive stars that have formed in the last 10 million years and, likely, due to the interaction. This doublet will serve as our evidence for where the galaxy is undergoing its starburst.

If we are unable to recover the [OIII] doublet, we will use *H*α to resolve the star formation occurring across the entire galactic disk. We will then conduct a comparison between the total star formation we find across each of our targets. By then controlling for stellar mass and stage, we will look for any enhancement through each stage. While this will be a small sample, it will be direct observations of the star formation through each.

Using the WEAVE exposure calculator, assuming optimal seeing of 1.2” and optimal airmass conditions we expect to require 1 hour of exposure on each target for a SNR of 10 across each target. While the SNR in the disks of each galaxies will be very high, we are holding for a surface brightness of 20 mags / arcsec out to the galactic edge. Thus, the total exposure time required will be 16 hours or 2 nights, rounded up to 3 nights.

Notes on what I want to write here:

1. Basically, primary reason I want to use WEAVE here is the massive Field of View.
   1. The colossal FOV of the LIFU means that for the first time we can capture the entire system of these very local systems.
   2. Because these systems are so local, and so large in size, have not got IFU data for any of the given ones (besides Heart, used as comparison).
2. Extremely large, local galaxies will be an excellent use of WEAVE to show how we can get to the sub-kpc measurements of galaxy emission.
3. Each galaxy is a very bright one, with the dimmest target having a V band magnitude of 18 magnitude (double check this).
   1. Therefore, to get the outer edges of the disks should be easy.
   2. Tidal features will be no dimmer than mu = 21 mags/arcsec^2.
4. Can achieve a SNR of 50 with just two hours of exposure on each target.
5. Hence, asking for 32 hours exposure for full 16 targets. This is a total of 11 interacting systems that will be fully observed.