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 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. However, there is a key component of an interaction we are missing: that of the velocity. By not knowing the motion within the tidal features, 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 (ten 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 galaxies 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 of the model when 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 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 three 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 ten 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 *H*α and [OIII] lines in each arm. Both emission lines are evidence of new star formation, expected in an ongoing starburst, due to the birth of high mass, short lived O and B type stars. However, observing [OIII] is difficult depending on the age of the stellar population and relying solely on measuring *H*α leaves us susceptible to contamination from nuclear activity and other sources of ionisation in the galaxy, such as shocks. Thus, we can minimise these contaminants by measuring the [NII], [OII], *H*β and 4000Å break. The different emission lines allow us to identify and quantify this contamination, while the 4000Å break gives us a direct indication of the specific star formation rate in the fibre. *H*α is also readily absorbed by the interstellar medium but by measuring *H*β emission we can account and correct for this.

It is important to note that using WEAVE gives us a unique opportunity to investigate where and when a starburst 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 the line of sight.

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 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 sixteen 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 ten systems we propose to observe are from a parent sample of sixty fully constrained interacting systems by [Holincheck et al. (2016)](https://ui.adsabs.harvard.edu/abs/2016MNRAS.459..720H/abstract). The full sample of sixty is a subset (primarily) from the [Arp (1966)](https://ui.adsabs.harvard.edu/abs/1966ApJS...14....1A/abstract) catalogue of interacting galaxies. Each of these systems is well known, and well studied. In fact, the [Holincheck et al. (2016)](https://ui.adsabs.harvard.edu/abs/2016MNRAS.459..720H/abstract) sample is one of the largest fully constrained samples of interacting galaxies to date, with the full orientation, orbital, total mass and interaction history found. Thus, our subsample of ten systems is selected based on knowing exactly the stage at which they are in the interaction. The full range of redshifts these interacting systems exist at are z = 0.008 – 0.04, meaning that there is no surface brightness dimming of their tidal features. Their apparent magnitudes ranges from 13.28 < g(mag) < 15.58 . Selecting such systems allows us to gain reasonable signal-to-noise ratios (S/N) down to a very dim magnitude (23) with a much shorter exposure time than would be required of smaller systems at high redshift.

This is our primary argument for using WEAVE’s large integral field unit (LIFU) to observe these systems. The large field-of-view (FoV; 90” × 78”) will allow us to make measurements of both the disturbed galactic disks and the tidal features. Thus, allowing us to see the direct connections between the galactic disk and the tidal features without making multiple observations. As an illustration of the improvement in FoV we will achieve in using WEAVE, we attach Figure 1. The left hand panels of Figure 1 shows the FoV and the resultant *H*α map of the Arp 239 system observed using MaNGA. First, the FoV is so narrow that only the disk of the interacting system is observed, with the *H*α map only revealing a rotating disk with limited resolution. The right hand panel shows the full FoV that will be achieved with WEAVEs LIFU. Not only will we fully explore the disk of the primary galaxy, but we will also reveal the kinematics within the tidal features themselves and parts of the secondary disk.

Only two of our proposed systems have been previously observed with MaNGA: Heart and Arp 239. We intend to use these as bench marks in comparing improvements in resolution and FoV between WEAVE and MaNGA. We anticipate measuring each of our systems to a resolution of 0.5kpc – 2.2kpc per fibre (dependent on galactic redshift). This will be more than sufficient to measure the gas kinematics within the galaxy, as well as to localize the star forming regions within it. We say this comparing to previous works (e.g. [Moreno et al. 2015](https://ui.adsabs.harvard.edu/abs/2015MNRAS.448.1107M/abstract); [Spindler et al. 2018](https://ui.adsabs.harvard.edu/abs/2018MNRAS.476..580S/abstract)). None of our proposed systems have been observed with other large IFUs such as CALIFA ([Sánchez et al. 2012](https://ui.adsabs.harvard.edu/abs/2012A%26A...538A...8S/abstract)) or SAMI ([Fogarty et al. 2014](https://ui.adsabs.harvard.edu/abs/2014MNRAS.443..485F/abstract)).

To measure the internal kinematics of each galaxy, we propose to use the low resolution version of the red arm of the LIFU to observe *H*α emission. The wavelength range observable by this arm covers the potential range of emission from our proposed systems (6623Å < *H*α < 6827Å). Upon correcting for the redshift of the galaxy, we will use the penalized pixel-fitting method spectra fitting code ([Cappellari & Emsellum 2004](https://ui.adsabs.harvard.edu/abs/2004PASP..116..138C/abstract)) to derive the velocities of the gas in each fibre by comparing to spectral energy distribution templates. Thus, we require our emission lines to be well resolved. This puts a lower limit of a S/N of 10 to ensure this. The dispersions of the red arm is 0.11Å / pix, translating to a velocity resolution of 5 km/s. From simulations, we expect the bulk motions within these galaxies to be in the range of hundreds of km/s, ensuring that we will measure accurate kinematics.

We will also use the measure of *H*α as a proxy for measuring the star formation rate across the entire galaxy. *H*α ionization is primarily caused by high mass OB type stars which dominate the light emitted in young stellar populations. These stars only exist for approximately 10 millions years, and therefore, their existence and ionization are sure signs of recent star forming activity. However, there are two important issues with using *H*α as our primary signature for star formation. First, such emission is readily absorbed by the interstellar medium, and therefore we must make corrections to our observations using *H*β emission. Second, *H*α ionization is not purely from star formation, but can also be from nuclear activity and internal shocks. It is likely that many of our targets host an active galactic nuclei (AGN) and would therefore contaminate our measurements of star formation from *H*α. We will remedy this potential contamination by using the blue arm of the LIFU.

While AGN contamination may be an issue for some of star formation measurements, we will be able identify such areas of contamination using other emission lines. Specifically, we will use the [OIII], [NII] and *H*β emission and the *Dn*4000 break that are well covered by also using the red arm of the LIFU. The ranges are as follows 5003Å < [OIII] < 5156Å, 6643Å < [NII] < 6848Å and 4904Å < *H*β < 5055Å. Using these lines, we will be able to identify regions in each galaxy which are specifically star forming, those which are ionized due to AGN and those which are a combination of the two.

For those regions which are not purely star forming, we will use the 4000Å-break(*Dn*4000; [Brinchmann et al. 2004](https://ui.adsabs.harvard.edu/abs/2004MNRAS.351.1151B/abstract)) to measure the star formation rate of the region. This parameter is the ratio of flux before the break to after the break. It is well used in this precise instance, and has a tight relation with the specific star formation rate of a region ([Spindler et al. 2018](https://ui.adsabs.harvard.edu/abs/2018MNRAS.476..580S/abstract)). This allows us to estimate the SFR in a contaminated fibre, and not have to simply remove it.

As stated previously, to measure the velocity field within each galaxy and the localized star formation, we need well resolved spectral lines with a high S/N. Due to the wide range of wavelengths we require to observe to account for AGN contamination, we must use the low resolution version of the LIFU. With the assumption of a seeing of 1.2” and a sky brightness of 21 (dark) in the V band, we will require an exposure of 5400s per target for a S/N of 10 at 23 mags / arcsec2. This calculation used the WEAVE exposure time calculator. Thus, accounting for further overheads, we calculate we can observe all 16 targets in 4.5 (rounded up to 5) nights in mid February 2024.

Figure 1 Caption:

The change in FoV from MaNGA to WEAVE.