The Star Formation Distribution in Interacting Galaxies

Summary of Proposal (Max 150 Words)

Galaxy interaction is a fundamental driver of galaxy evolution. A key question surrounds the star formation during interaction. While it is primarily agreed that interaction enhances star formation in the involved galaxies, it is not obvious when in the interaction and where in the galaxy this enhancement occurs. We propose to observe 14 targets, covering 12 systems of interacting galaxies at 4 stages of interaction. These are local galaxies (with a maximum z = 0.04) with very large angular sizes. We propose to use WEAVE`s LIFU, with its large FoV, to obtain full IFU information, for the first time, of these systems. We will localise star formation and quantify any enhancement. Using the same observations, we will measure the internal kinematics of these galaxies and, most importantly, their tidal features. This will allow us to strengthen our constraints on their interaction history.

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 (e.g. [Toomre & Toomre 1972](https://ui.adsabs.harvard.edu/abs/1972ApJ...178..623T/abstract)), increases in star formation (e.g. [Moreno et al. 2021](https://ui.adsabs.harvard.edu/abs/2021MNRAS.503.3113M/abstract)) which often leads to quenching (e.g [Smethurst et al. 2018](https://ui.adsabs.harvard.edu/abs/2018MNRAS.473.2679S/abstract)) and triggers supermassive blackhole growth (e,g. [Hopkins et al. 2008](https://ui.adsabs.harvard.edu/abs/2008ApJS..175..356H/abstract), [Ellison et al. 2011](https://ui.adsabs.harvard.edu/abs/2011MNRAS.418.2043E/abstract)). However, how the underlying parameters of an interaction (relative sizes, and approach velocities, angles of incidence, etc) influence these processes or which tidal features form is poorly understood.

A primary question is where / if a starburst occurs in a galaxy interaction. Often, this question is answered with simulations. Is it primarily during the interaction (Wilkinson et al. 2018) or only upon coalescence (Hopkins et al. 2013)? Does a starburst even happen at all (Moreno et al. 2015)? 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), or are there significant increases in star formation in the galactic disk and tidal features (Sparre et al. 2022)? Direct observations localising star formation in interacting galaxies are very limited and, therefore, the answer remains elusive. **By using WEAVE, and its uniquely extended field-of-view (FoV), we have an opportunity to significantly enhance our understanding.**

We have conducted preliminary work using a subset of interacting galaxies from the [O`Ryan et al (2023)](https://ui.adsabs.harvard.edu/abs/2023ApJ...948...40O/abstract) catalogue. We cross matched this catalogue with the COSMOS2020 ([Weaver et al. 2023](https://ui.adsabs.harvard.edu/abs/2022ApJS..258...11W/abstract)) catalogue for photometric parameterisation. We then classified these systems into four different stages of interaction, with each stage representing a different chronological part of the interaction history. Thus, we can quantify when, in an interaction, the star formation enhancement begins. In Fig. 1, we plot the star formation with stellar mass controlling for stage. The disappearance of the red sequence of galaxies in the later stages indicates a generally increasing star formation rate with stage. Thus, implying star formation enhancement occurs primarily later in the interaction. **But, we lack critical information about how this is quantitatively distributed, and e.g. how it follows the tidal features (or does not).**

The 12 systems we propose to observe (Fig. 2) are split across 14 pointings and are equally into stages of interaction and are of similar mass ratios and gas content. They are also a subsample of the sixty interacting systems from the Galaxy Zoo: Mergers ([Holincheck et al. 2016](https://ui.adsabs.harvard.edu/abs/2016MNRAS.459..720H/abstract)) project. Through combining citizen science approaches with a highly efficient N-body simulation code they fully constrained the parameters and interaction history of each of them. However, no full IFU data exists for them due to their angular size. With the large FoV of WEAVE, we are able to measure the full system with a single pointing.

To measure, and localise, the star formation throughout each galaxy we focus on the Hydrogen alpha (Ha) and [OIII] lines. These are evidence of new star formation due to the birth of high mass, short lived OB type stars. However, observing [OIII] is difficult depending on the age of the stellar population and relying solely on measuring Ha leaves us susceptible to contamination from nuclear activity and other sources of ionisation in the galaxy, such as shocks. Ha is also readily absorbed by the interstellar medium. We will minimise contaminants and account for absorption by measuring the [NII], [OIII], and Hydrogen beta (Hb). We will also measure the 4000A break for a direct indication of the specific star formation rate in a fibre.

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 FoV required to view these systems with an IFU (**and only available with WEAVE**) means that a full star formation or velocity map including their tidal features has never been created. With the furthest system (J155308.62+540950.4) being at z = 0.04, the worst resolution we will achieve is 2.12kpc / fibre.

A secondary goal of this proposal is to measure the internal kinematics of these systems. We have developed new software to automate the process of [Holincheck et al. (2016](https://ui.adsabs.harvard.edu/abs/2016MNRAS.459..720H/abstract)) within a rigorous statistical framework; allowing us to apply their constraining methodology to a much larger sample.

The software release paper (in prep.) uses the Galaxy Zoo: mergers sample as a fiducial dataset. However, we are missing a key component of an interaction: the velocity. As we do not know the bulk motion within the tidal features, we infer multiple peaks in the probability distribution from our models: particularly in the z-position and orientation.

We have conducted a preliminary investigation into the improvement we can attain, using the Arp 239 system as an example. This is one of only four interacting galaxies which has existing partial IFU data from MaNGA ([Bundy et al 2015](https://ui.adsabs.harvard.edu/abs/2015ApJ...798....7B/abstract)); the remaining fifty six lack any IFU data due to each galaxies large angular size and the FoV that would be required to observe them. With the limited IFU data of only the core of the galaxy (due to the limited FoV of MaNGA), we infer the probability distributions in Fig. 3. On the left and right panel we show constraints of the z-position, velocity orientation each system without and with access to kinematic information, respectively. We find significant improvements on our constraint on the z-position, breaking the degeneracy, and velocity when kinematic information is available. In the orientations, we also find tighter constraints and reduce the four-fold degeneracy to a two-fold one. **However, due to no existing velocity information of the tidal features we cannot completely remove this degeneracy.**

With kinematic information for the tidal features, our software can incorporate 3D information and further constrain the correct z-position, and reduce the two-fold degeneracy in the orientations from the direction of rotation of the galaxies. **This significantly improving our understanding of the Arp 239 system and the applicability of the software more generally**.

This is an excellent pioneering use of WEAVE, to demonstrate it can break boundaries 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 kinematic information to our parameterising software. The second will be on studying precisely where and when star formation is enhanced in merging systems.

Figure 3 Caption:

Probability distribution of the best fit parameters for the Arp 239 (J134139.32+554014.6; target 11) interacting galaxy system. This is a system that has just passed pericentre. Shown on the left side is the initial probability distribution of numerous parameters of the interaction with no velocity information available. On the right side is the same, but with velocity information available. With velocity information from IFU data, we have a significant improvement on our constraints.

Figure 1 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. Each stage is: stage 1 - approaching pericentre, stage 2 - passed pericentre, stage 3 - at apocentre, stage 4 - Coalescence. The removal of the red sequence with stage indicates that star formation enhancement is occurring in the latter stages of the interaction. However, where this enhancement is occurring remains unknown. Using WEAVE, we will quantitatively compare the star formation enhancement between stages and, more importantly, define where this enhancement is occurring.

Figure 2 Caption:

The targets proposed. In total, there are 14 targets measuring 12 different interacting systems. Due to the very large FoV of all WEAVE LIFUs, we will able to observe the full extent of all of these systems for the first time with IFUs. Each target box is approximately the FoV of WEAVE.

Technical Justification (max 1200 Words)

The 12 systems, split into 14 targets, we propose to observe are from a parent sample of 60 fully constrained interacting systems by [Holincheck et al. (2016)](https://ui.adsabs.harvard.edu/abs/2016MNRAS.459..720H/abstract). This is a subset from the [Arp (1966)](https://ui.adsabs.harvard.edu/abs/1966ApJS...14....1A/abstract) catalogue of interacting galaxies. Each system 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 12 systems is selected based on knowing exactly the stage at which they are in the interaction. The systems range in redshift between z = 0.008 - 0.04, well within the regime where the observed surface brightness does not depend on redshift. Their apparent magnitudes range from 13.28 < g(mag) < 15.58. Thus, we can gain reasonable signal-to-noise ratios (S/N) down to a magnitude (>21) with shorter exposure times 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`` x 78``) allows us to make measurements of both the disturbed galactic disks and the tidal features. This gives us direct connections between the galactic disk and the tidal features without making multiple observations. Figure 1 illustrates the improvement in FoV we will achieve in using WEAVE. The left panels of Figure 1 shows the FoV and the resultant Ha map of the Arp 239 system observed using MaNGA. The MaNGA FoV only captures the disk of the interacting system, with the Ha map only revealing a rotating disk with limited resolution. The right panel shows the full FoV that will be achieved with the WEAVE LIFU: providing complete coverage of the galactic disks and tidal features.

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. Not only will WEAVE be able to observe the full system, but we anticipate measuring each to a resolution of 0.5kpc – 2.2kpc per fibre. This will be more than sufficient to measure the gas kinematics within the galaxy, and to localize the star forming regions within it (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 IFUs larger than MaNGA 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 will use the low resolution mode of the red arm of the LIFU to observe Ha emission. The wavelength range observable by this arm covers the potential range of emission of our targets (6623A < Ha < 6827A). 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 minimum resolution (the red arm) is 1.52A, from experience the authors can identify the emission centroid to 1/10th of a pixel corresponding to a velocity resolution of 6.91 km/s. We expect the bulk motions within these galaxies to be in the range of hundreds of km/s - at least an order of magnitude above our potential errors.

Ha will also act as an indicator for measuring the star formation rate across the entire galaxy. Ha 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 million years, and therefore, their existence and ionization imply recent star forming activity. However, using only Ha has its limitations. First, such emission is readily absorbed by the interstellar medium, and therefore we must make corrections to our observations using Hb emission. Second, Ha ionization is not purely from star formation, but also nuclear activity and internal shocks. It is likely that many of our targets host an active galactic nuclei and would therefore contaminate our measurements of star formation.

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 Hb emission and the *Dn*4000 break that are well covered by also using the red arm of the LIFU. The ranges are as follows 5003A < [OIII] < 5156A, 6643A < [NII] < 6848A and 4904A < Hb < 5055A. These ranges that are not covered by the red arm, are readily covered by the blue arm.

For those regions which are contaminated, we will use the 4000A-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, and has a tight relation with the specific star formation rate ([Spindler et al. 2018](https://ui.adsabs.harvard.edu/abs/2018MNRAS.476..580S/abstract)).

For our purposes, we need well resolved spectral lines with a minimum S/N/Ang=10. Due to the wide range of wavelengths we must to observe, we will use the low resolution mode of the LIFU. With the assumption of a seeing of 1.2`` and a sky brightness of 21.4 (dark) in the V band, we will require an exposure of approximately 5400s per target for a S/N/pix = 10 and S/N/Ang = 21.61 at 22 mags / arcsec2. This calculation used the WEAVE exposure time calculator. Thus, the on target observing time for the 14 targets would be 2.62 (rounded up to 3) dark nights mid February 2024. If overheads are not included in the calculation, we would estimate that per target would require 8100s total time, requiring 3.94 (rounded to 4) nights of observing. Assuming Grey time (sky >= 20.8 mag/arcsec2), we find that an acceptable S/N/pix=17.82 and S/N/Ang=9.07 would be achieved in the same observing time.

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Figure 1 Caption:

Example of the improvement in field-of-view (FoV) of between MaNGA and WEAVE when observing the Arp 239 interacting system. Left panel, top: The FoV of MaNGA on the galactic disk. Left panel, bottom: The Ha map of the Arp 239 revealing a rotating disk. With this limited FoV, we do not capture any of the tidal features in the observation and lose this crucial information of the system. Right panel: the expected FoV of WEAVE. With the large FoV of the LIFU, we will not just observe the primary galaxy and its tidal features but the entire system in one pointing.